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INSTRUMENTATION GROUNDING AND NOISE MINIMIZATION HANDBOOK

TECHNICAL REPORT NO. AFRPL-TR-65-1

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ERRATA SHEET

FOR

INSTRUMENTATION GROUNDING

AND NOISE MINIMIZATION HANDBOOK

TECHNICAL REPORT NO. AFRPL-TR-65-1

This errata sheet forms a part of the "Instrumentation Grounding and Noise Minimization Handbook," Technical Report No. AFRPL-TR-65-1, dated January 1965.

Page 1-3: COMMON-MODE VOLTAGE: The word "miaximum" should read "maximum".

Page 2-5: Second paragraph; change the word "premeability" to "permeability".

Page 2-20: Second paragraph; the reference "signal [12]" should be reference "signal [13]".

Page 2-22: Paragraph 2.1.6.5 "k = Boltzmans Contant" should read "k = Boltzmans Constant".

Page 2-25: Figure 2-13; the values "C_S and C_O" should be "e_s and e_o".

Page 2-33: Paragraph 2.2.1.2.1, the word "realy" should read "relay".

Page 2-39: Third paragraph; change "A significant movement" to "A significant improvement".

Page 2-55: First paragraph; the word "appose" should be "oppose".

Page 2-62: Last paragraph; delete reference to the Bibliography and substitute the following: "refer to the article of May 1963, Electro Technology, titled "Specification and Testing of Shielded Transformers" by Bernard I. Sommer and Gerald W. Plice".

Page 2-73: Equation $CMR = E_{cm} E_{nm}$ should be $CMR = \frac{E_{cm}}{E_{nm}}$

and

$CMR \frac{Z}{(R_2 - R_1)}$ should be $CMR = \frac{Z}{(R_2 - R_1)}$

Page 2-93: First paragraph; second line, change "require that Z_1 by less than 2.7 picofarads" to "require that Z_1 be less than 2.7 picofarads".

Page 2-95: The value "e = Coulomb change" should read "e = Coulomb charge".

Pages 2-99, 2-100, 2-101, 2-104, 3-13: Figures 2-73, 2-74, 2-75, 2-78 and 3-6 add the term "Recommended" to these figures.

Page 5-2: Figure 5-1; change FILTER 500 cy to FILTER 500 CPS and A/C CONVERTER to A/D CONVERTER.

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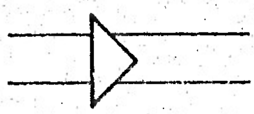

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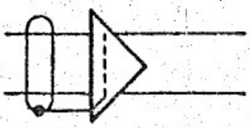

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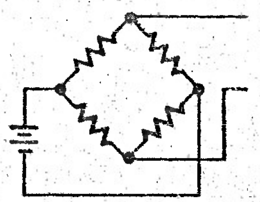

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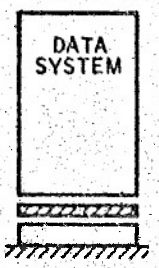

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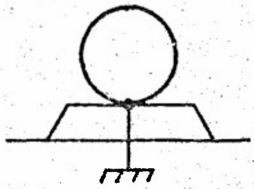

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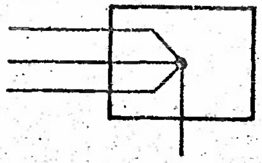

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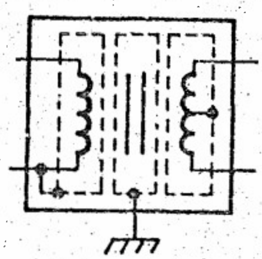

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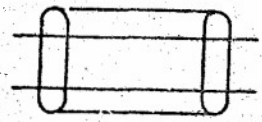

Two Conductor, Shielded Cable

FOREWORD

At the present time instrumentation systems are undergoing a rapid change brought about by advances in the state-of-the-art in electronics, electronic systems, and by the stringent data requirements of space programs. One particular area of significant importance in obtaining reliable and accurate data at high acquisition rates which has not been able to keep stride with these advances, is the proper grounding of instrumentation circuits, both analog and digital. Since there are many methods of instrumentation grounding in practice, a unified approach to this problem is urgently needed. The number of different approaches used in grounding indicates very clearly that present day grounding design is still somewhat of an art and continues to reflect the initiative, imagination, and experience of the particular individual who designed or implemented the system or facility.

Material presented in this handbook is general in nature with sufficient information given that an instrumentation engineer or a facility power engineer may apply to his more detailed requirements the fundamentals necessary which will produce a low noise and high accuracy data acquisition system. The information is primarily directed toward modern digital data acquisition systems which are becoming the byword for high speed and accuracy in data acquisition. Analog data acquisition is a very necessary means of obtaining "quick-look" data required to monitor the progress of test firing, launch, etc. Analog systems are considered and details are given for the proper grounding of these devices relative to the elimination of common-mode voltages.

Because of the many inter-relationships of instrumentation subsystems the reader will find areas of duplication. However, this redundancy is necessary in order that continuity be preserved and that as many aspects as possible of the subject be presented so that the respective viewpoints of each interested reader would be considered.

This handbook has been written to bring together a common reference for the solution of grounding problems in instrumentation systems and in power systems where the power system is installed nearby and for the purpose of supplying primary power to the data facility.

This handbook is the result of an Air Force sponsored study of grounding techniques for the minimization of instrumentation noise problems and represents the first known comprehensive effort of its kind in the field of data instrumentation and acquisition. Further work and study into the nature of grounding is suggested in order that a more complete understanding of earth currents and stray potentials be obtained.

It is hoped that this handbook will provide the basis and, more important, the incentive for further study into this often neglected and very important area of data instrumentation and acquisition.

ACKNOWLEDGEMENTS

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1. INTRODUCTION

The information covered in this handbook is based on laboratory experiments conducted and directed by a number of well qualified data acquisition and data reduction systems engineers. This section contains the Safety and Code Requirements and a glossary of the major terms used throughout this handbook. Section 2 is divided into two categories: (1) causes of noise, and (2) noise reduction and prevention. In the first part, all major noise causes are described and defined. The second part then presents methods of noise prevention or reduction based on theoretical as well as imperical knowledge of grounding and noise reduction and prevention. Questions which will be answered are: What is the best grounding technique to use with analog and digital data acquisition systems? What type of shielding is required in electromagnetic fields and electrostatic fields? What effect does twisting of data instrumentation lines have against noise? Should isolation by provided between instrumentation grounds and power grounds via isolation transformers? What is common mode voltage and what are its effects on data instrumentation? What is the importance of a good earth connection for grounds? Section 3 describes the recommended system design practices which have been studied and concluded to be of most value in the selection of a data instrumentation facility, power usage and location within the facility area, and the overall grounding philosophy for both instrumentation and power circuits, including the relative values of incadescent lighting vs florescent lighting. The basic National Electrical Codes are mentioned and deviations for the purpose of reducing noise are given in detail. Section 4 gives the grounding principles which are best suited for all major subsystems of a somewhat sophisticated data acquisition system. Also included are the peculiar characteristics of each subsystem as to its susceptibility to noise. This section also discusses the importance of analog and digital circuit isolation and separation of grounds, proper grounding of cabinets and structures, and how a common mode voltage can be reduced to a minimum. Section 5 is a compilation of good practices necessary in the modification, operation, and maintenance of a low noise and highly accurate data instrumentation and acquisition system.

1.1 SAFETY AND CODE REQUIREMENTS

The design and construction of any test facility and its associated equipment should provide, under all conditions of operation, maximum practical safety to personnel, property, and equipment. The purpose of the various electrical codes is to specify the minimum requirements which electrical systems must meet to result in a safe installation. The introduction to the National Electrical Code states its purpose as follows:

"The purpose of this Code is the practical safeguarding of persons and of buildings and their contents from hazards arising from the use of electricity

for light, heat, power, radio, signalling, and for other purposes."

"This Code is not intended as a design specification nor an instruction manual for untrained persons."

In essence, the National and Local Electrical codes specify minimum requirements for a safe electrical installation while permitting and encouraging the design and installing agencies to exceed code requirements, where desired, to produce a more efficient, convenient, and/or expandable electrical installation.

The applicability of electrical codes varies with the locality. Some states have no codes of their own and require that electrical installations conform to the National Electrical Code which is a standard of the National Board of Fire Underwriters. Other states publish an electrical code, either separately or as part of a general building code, which broadly embraces the National Electrical Code but specifies certain exceptions. Some states publish a complete, separate, independent electrical code which may differ from and be more stringent than the National Electrical Code on any particular item. Some counties and municipalities also publish electrical codes which govern installations within their boundaries.

The enforcement and interpretation of electrical code requirements are generally the responsibility of a local organization, such as a Department of Industrial Safety, formed by the city, county, or state government issuing the applicable code. In the case of a facility which will be located on U.S. Government property, remote from major population centers, the state or local officials usually relinquish inspection and enforcement of code requirements and this task falls to the federal agency responsible for the installation (such as the U.S. Army Corps of Engineers or the Base Facilities Engineering Group). In such instances, the federal agency generally requires compliance with the National Electrical Code.

Because of the "patchwork" nature of electrical code applicability and since most of the instrumentation and data acquisition systems affected by this handbook will be installed on U.S. Government property, subsequent references to the "Code" will mean the National Electrical Code. Those facilities which must conform to state or local electrical codes will require additional investigation in the early design stages to assure compliance with all requirements of the local code.

1.2 GLOSSARY

ACCURACY: The numerical difference between any value and the true value. Applied by transferance to the instrument or system producing the value. Distinguished from precision:

1. Instrumental - the accuracy of a measurement after the errors caused by elements external to the instrument are removed. A measure of the accuracy of the instrument proper.

2. Transducer - the ratio of the error to the full-scale output (expressed as "within percent of full-scale output") or the ratio of the error to the output, expressed in percent.

ALTERNATING CURRENT (AC): Electric current that reverses its flow in each direction at regular alternate intervals. The frequency of the change in flow is expressed in cycles per second.

AMPLIFIER BUFFER: An amplifier used to isolate the output of any device; e.g., oscillator, from the effects produced by changes in load from subsequent circuits.

ANALOG-TO-DIGITAL CONVERTER (ADC): An instrument used to convert analog voltages, either low level (10 MV full scale) or high level (10 V full scale) voltages to digital binary coded values which are proportional to the analog input voltages.

BALANCED LINE: A transmission line consisting of two conductors in the presence of ground, capable of being operated in such a way that the voltages of the two conductors are equal in magnitude and opposite in polarity with respect to ground, the currents in the two conductors are equal in magnitude and opposite in direction.

COMMON MODE INPUT: Common-mode input is defined as that signal applied in phase equally to both inputs of a differential amplifier.

COMMON MODE GAIN: Common-mode gain is defined as the ratio of the common-mode output voltage divided by the common-mode input voltage.

COMMON MODE REJECTION: The ability of an amplifier to reject a signal common to both its input terminals. Common-mode rejection (CMR) is the ratio of the applied common-mode input voltage to the equivalent normal-mode output signal it produces.

COMMON MODE VOLTAGE: That amount of voltage common to both input lines. Usually, a miaximum voltage is specified which may be applied without breaking down insulation between the input circuit and ground.

CONDUCTED INTERFERENCE: Caused by the coupling effect of capacitance, resistance, and inductance to the source of interference.

ELECTROMAGNETIC INDUCTION - or INDUCTIVE PICKUP: Refers to interference coupled to the measuring circuit through magnetic fields.

ELECTROSTATIC INDUCTION: Sometimes referred to as capacitive induction, is due to the unavoidable capacitance between the instrument or its wiring and the surroundings.

FACILITY POWER SYSTEM: That portion of the electrical power distribution and utilization system on the secondary side of the main electrical service transformer(s) for the test facility.

GROUND: A conducting connection, whether intentional or accidental, between an electric circuit (orequipment) and earth, or to some other conducting body which serves in place of the earth.

GROUND, ANALOG: Associated with the input circuits of an instrumentation system. Analog ground circuits are isolated from one another and are connected together at only one point, (e.g. ground bus, plate, etc.) and then, if required, this point can be connected to earth.

GROUND, CIRCUIT: That portion of an electrical or electronic circuit which is kept at essentially zero volts with respect to the power supply voltages. This ground circuit is not necessarily connected to earth. An electronic circuit will perform whether or not its ground circuit is connected to earth.

GROUNDED NEUTRAL: The neutral wire is metallically connected to ground.

GROUND LOOP: A path through which current may flow from any starting point through a system and back to the original starting point.

GROUND, POWER: The power ground as defined by the National Electrical Code is any electrical connection between power system conductors (usually the neutral conductors) conductor enclosure or equipment enclosure and earth with 25 ohms or less resistance to earth. This ground is for the protection and safety of personnel.

ISOLATED DIFFERENTIAL AMPLIFIER: A differential amplifier whose input signal lines are conductively isolated from the output signal lines and chassis ground. An isolated differential amplifer is a differential amplifier, but not all differential amplifiers are isolated.

JUNCTION OR THERMAL POTENTIALS: Can contribute to error and are of special concern in handling low level DC signals. Items such as the cable flexing

noise that arises in the use of pH meters and ion chambers might also be placed in this category.

N. E. C.: National Electric Code, which stipulates the use of wire and cable in buildings and factories. Most city electrical codes are derived from it. It has been compiled by the fire underwriters and wire and cable manufacturers.

NOISE: Any disturbance or spurious signal which modifies the transmission, indicating or recording of the desired data.

1. Amplitude of. When impulsive type noise is of random occurence and so closely spaced that the individual wave shapes are not separated by the receiving equipment, then the noise has the wave shape and characteristics of random noise. Random noise amplitude is proportional to the square root of the bandwidth.
   If the impulses are separated, the noise no longer has the wave shape of random noise and its amplitude is directly proportional to the bandwidth of the transmission system.
2. Electrical. Unwanted electrical energy other than cross talk present in a transmission system.
3. Gaussian. A noise whose power is distributed according to normal or Gaussian distribution.
4. Impulse. Noise generated in discrete energy bursts, not of random nature, and which has a characteristic wave shape of its own.
5. In Measurements. Generally, Random Errors and other errors that have a relatively high frequency (short period) compared to that of other errors such as most Systematic Errors and as compared to the highest frequency component of the phenomenon observed.
6. Random. Noise in which the frequency and phase of the components vary entirely at random. It is characterized by a peak to average noise level ratio in the order of 3:4 to 4:5. This is a broadband type noise. Thermal and shot noise are typical.
7. White. A noise whose power is distributed uniformly over all frequencies and has a mean noise power unit bandwidth. Since idealistic white noise is an impossibility, bandwidth restrictions have to be applied.

PRECISION:

1. A measure of a reproductability with which one instrument (or several instruments of the same type) can reproduce repeatedly measurements of the same quantity. If the precision is high, such results will lie within a narrow range.

2. Adapted for extremely accurate scientific measurements. It is not, however, a guarantee of accuracy (negligible error), because precision refers to the measuring instrument and does not cover external sources of error inherent in the measuring method.

3. Computation. The degree of exactness with which a quantity is stated, as constrasted with ACCURACY, which is the degree of exactness with which a quantity is known or observed.

4. Of Measured Data or of a Measuring Instrument. In general, the uniformity of data from repeated measurements of the same constant phenomenon. In the case of a constantly changing phenomenon, the word precision has a similar meaning. The best measure of precision in the latter case is the STANDARD ERROR OF ESTIMATE (S). The smaller S is, the higher the precision. Precision usually is a function of the time interval between measurements and so should be qualified. See ACCURACY.

RADIATED INTERFERENCE: Caused by radiation of magnetic field from a transmitter and induced or "picked-up" by a receiver located at a considerable distance from the transmitter.

SHIELD: A metallic sheath placed around an insulated conductor or group of conductors to protect against extraneous currents and fields. Generally this shield is a metallic braid, but it could be spiraled copper, aluminum-backed Mylar tape, or conductive vinyl or rubber.

TRANSDUCER: A device which converts the energy of one transmission system into the energy of another transmission system. A loudspeaker and a phonograph pick-up are two examples of transducers, the former changes electrical energy into acoustical energy, and the latter changes mechanical into electrical energy.

2. SYSTEM DESIGN

2.1 CAUSES OF NOISE

2.1.1 POWER EQUIPMENT AND TRANSMISSION SYSTEMS

Electrical power generation, utilization, control, transmission, and distribution equipment and conductors are all potential sources of instrumentation system noise. The interference generated by power system sources can be divided into two categories:

a. Noise at power frequency and harmonics of the power frequency.
b. Broad spectrum radio-frequency noise.

Noise of the former classification is caused primarily by utility and facility power transmission and distribution lines. The latter type of noise is most often associated with generation, utilization and control equipment, and with power utility high voltage transmission and distribution lines.

2.1.1.1 Noise at Power Frequency

Noise at the power frequency and harmonics of the power frequency appears in data transmission lines by virtue of the resistive, inductive, and capacitive coupling between the data transmission lines and power transmission and distribution lines. Parallel conductors exhibit both mutual inductance and capacitance between one another. Since power conductors carry relatively large currents and operate at higher voltages than data transmission lines, power frequency voltages may appear on the data transmission lines through this coupling and cause considerable noise problems. In addition, if care is not taken to properly ground the data acquisition system (See Sections 2 and 3) ground currents associated with the power system may be coupled to the data transmission system resistively, capacitively and inductively. Power frequency noise can be minimized by eliminating or minimizing the amount of coupling between power conductors and data transmission conductors. The effects of coupling between circuits and of ground currents are covered in greater detail in other sections of this handbook.

2.1.1.2 Radio-Frequency Noise

Broad-band radio-frequency noise is caused by some rotating equipment, power and control switching devices, electric discharge lamps, and high voltage power transmission lines and equipment. This is due to the arcing and corona effects produced by this type of equipment.

Rotating Equipment which contains brushes and commutators or slip rings is subject to arcing to varying degrees, depending upon the basic design of the equipment. A motor or generator utilizing a commutator (such as a "universal" motor

often used in portable power tools or a DC moto r generator) will generate an arc each time a commutator bar slides from under a brush. Careful design of the equipment will minimize arcing and it is generally desirable to do so not only from the standpoint of radiated interference, but from a maintenance standpoint as well. Excessive arcing will result in a burned commutator and shortened brush life. Another source of arcing in commutator and slip ring machines is brush bounce which is due to poor design and maintenance. Arcing can sometimes occur in rotating equipment which does not contain commutators or slip rings due to the discharge of a build-up of static charge between the rotor and stator. Such arcing is generally less serious than that produced by commutators or slip rings because it occurs less frequently, is of lower energy, and can be eliminated by the use of conductive bearing lubricants or grounding brushes. Noise from rotating machinery can be minimized by using induction motors (which contain neither commutators nor slip rings) wherever possible and by excluding rotating equipment from areas containing low-level instrumentation circuits.

Power ... ol switching equipment such as switchgear and motor control centers is a source of electric arcs and switching transients in normal operation. The majority of power circuits being switched in a typical instrumentation test facility are inductive. When an inductive circuit is opened, a large part of the energy stored in the inductive field is dissipated as an arc at the opening contacts. The noise produced can best be minimized by placing the switched power circuits as far as possible from the susceptible instrumentation circuits. Where isolation is not possible, arc suppression devices can be applied although degradation in relay operation sometimes results. Arc suppression devices introduce a delay in the release time of relays, a characteristic which might be detrimental in some applications.[1]

Another source of radiated and conducted radio frequency noise is electric discharge of lighting fixtures such as fluorescent and mercury vapor fixtures. The generation of noise is due to the action of an arc which exists at the cathode of the lamp. One solution is to use incandescent fixtures in areas which contain equipment or data transmission lines susceptible to radio frequency interference. However, the present tendency toward increased illumination levels and the relatively greater effeciency of electric discharge fixtures make this solution unacceptable in many cases. The noise from the arc is transferred to susceptible circuits by direct radiation from the arc and by radiation and conduction from the circuit feeding the fixture. Attenuation of these two transmission paths is treated separately.

a. Radiation from the arc can be attenuated either by placing the noise source as far as possible from the instrumentation circuits (spatial isolation) or by shielding. Generally, if a fixture is more than ten feet away from susceptible circuits, the effect on the circuit will be negligible.[2] This solution will almost always be applicable to mercury vapor fixtures which, because they

are an intense, high-output source, are usually mounted high above the area to be lighted. Where fluorescent fixtures must be mounted in areas sensitive to radio frequency noise, it is possible to obtain fixtures with a diffuser or bus panel which incorporates a transparent conductive coating and careful bonding between the diffuser and fixture reflector. Such a fixture, when equipped with a line filter, will meet military specifications MIL-I-16910A, MIL-I-6181D and MIL-I-26600.

b. Radiation and conduction of noise through electrical wiring to electric discharge fixtures is, in some ways, more serious than radiation directly from the arc because the noise may be conducted a considerable distance from the source. The best way to block this path is by installing a filter in the line at the fixture. Such filters are commercially available.

High voltage transmission lines and hardware are sources of radio frequency noise in the form of corona. The formation of corona on transmission lines is influenced by many variables, some of which are:

a. Voltage

b. Conductor diameter

c. Type of conductor

d. Surface condition of conductor

e. Line configuration

f. Design and installation of hardware

g. Weather

h. Barometric pressure

i. Temperature

The first six items depend primarily upon design and installation of the transmission line and, for a new line, can be controlled to produce minimum corona, subject to economic trade-offs and restrictions.

Corona and associated radio noise on a given transmission line may vary by a factor of 10 to 1 in a relatively short period under stable fair weather conditions. The variation between fair weather and rain or fog can be more than another order of magnitude.[3] To date, no simple relationship has been found which would enable the designer of a transmission line to predict accurately the worst case radio noise at a point along the line. Transmission line design for a tolerable radio noise level is based on comparisons and experience with existing similar lines for which the noise level and the significant parameters are known.[4] Values of radio frequency interference as low as 130 UV per meter and as high as 2200 UV per meter have been measured beneath 130 KV lines of different design under fair weather conditions.[5]

Radio frequency noise due to high voltage transmission line corona can be minimized by spatial isolation and by careful line design and installation practices. Isolation is the only approach available for an existing line. As a rough-approximation, radio frequency noise from this source is attenuated at the rate of 0.1 to 0.3 db per foot out to 150 feet from the outer conductor. The approximate attenuation then drops off rapidly beyond this point. Typical values for a 230 KV line presently installed on the Bonneville Power Administration system in Washington State range from approximately 200 UV per meter immediately under the line to 10 UV per meter at a point 400 feet horizontally from the outer conductor.[6] The measurements were made at 800 KC with a quasi-peak meter under fair weather conditions. The second approach, that is, designing the transmission line for low corona should be followed for new lines passing within one or two miles of an area containing instrumentation circuits sensitive to radio frequency noise.

2.1.2 ELECTROMAGNETIC RADIATION

Principles of Electromagnetic Radiation - According to Faraday's Principle:

> "When a magnetic field cuts a conductor, or when a conductor cuts a magnetic field, an electric current will flow through the conductor if a closed path is provided by which the current can circulate."

This current will flow only while the magnetic field is changing or while the conductor itself is being moved through the magnetic field. (See Figure 2-1)

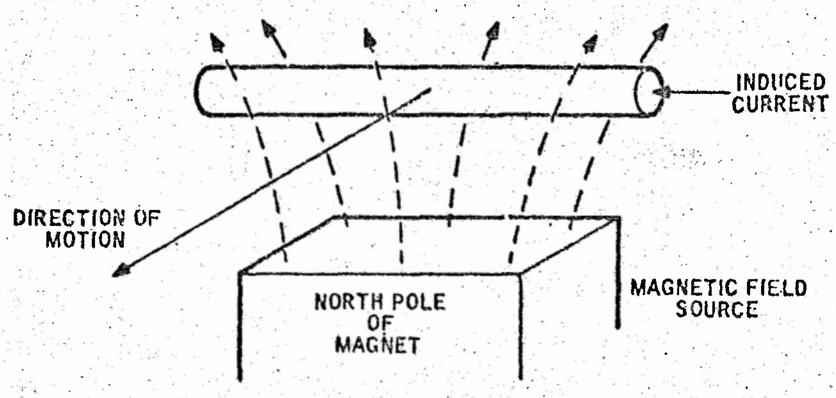


FIGURE 2-1
Electromagnetic Radiation

Thus, the value of induce voltage (e.m.f.) varies directly with the change in flux or flux cut and inversely with the time of cutting

$$\epsilon = -N \frac{d\phi}{dt} 10^{-8}$$

and for average values.

$$E = N\frac{\phi}{T}10^{-8}$$

The induced emf will be in volts with ϕ in Maxwells. N is the number of turns of wire in the loop or the number of conductors in series cutting the flux ϕ.

Since a conductor carrying a current is surrounded with a magnetic field, a simple way to vary the inductive field would be to vary the current either in the circuit (self inductance) or a nearby circuit (mutual inductance). An interesting property of self inductance is that the magnetic field will always be such that it opposes a change in current. So, the induced emf will aid the current if it is decreasing and oppose the current if it is increasing. If it is assumed that the premeability of the circuit is constant, then ϕ(flux) and i (current) are directly proportional and the expression

$$\epsilon = -L\frac{di}{dt}$$

is another way of expressing the fact that the induced emf is proportional to the rate of change of flux. L is the circuit inductance in Henries, ϵ is in volts, i in amperes, and t in seconds.

Now consider a circuit that is subjected to a magnetic field whose flux density is

$$B = \frac{\mu NI}{l}$$

where B = density in gauss = $\frac{\phi}{A}$

μ = permeability

N = Number of turns 1 for single closed circuit

I = current in circuit

l = distance to field source

The induced voltage in a circuit of area A and frequency $\omega = 2\pi F$ will be

$$E = \omega BA = \omega A\left(\frac{\mu NI}{l}\right)$$

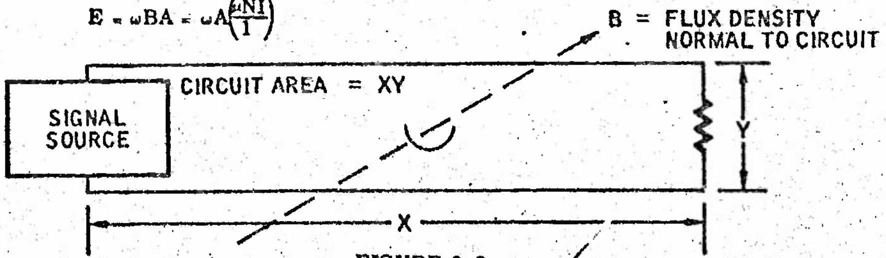


FIGURE 2-2
Induced Voltage

Therefore, it can be seen that there exists three basic considerations which are fundamental to the understanding of magnetically induced voltages in any circuit.

a. Rate of change of the field (frequency): the higher the rate of change the larger the induced voltage.

b. Circuit area, or circuit inductive reactance: the larger the circuit area the more induced voltage.

c. Distance between magnetic field source and circuit: the induced voltage is inversely related to the flux path (distance).

Magnetic fields can be generated from a variety of sources. The following is a partial list of the most common sources which are frequently found in a data instrumentation test area:

a. AC motors and transformers
b. AC power lines
c. Induction heaters and arcing contacts in AC power circuits
d. High in-rush circuits (e.g., relay solenoids, solenoid valves, etc.) and DC voltage switches (e.g., logic circuits, DC control levels, etc.)

Strong AC magnetic fields can be generated by AC motors and transformers, particularly those which carry large amounts of current in the order of 10 AMPS and more. Instrumentation cables, cabinets, transducers, and auxiliary equipment must be kept as far as possible from AC motors and high current AC distribution transformers which are not electromagnetically shielded and properly grounded. When an instrumentation cable passes through such a field it has been found that up to 170 UV of noise can be induced in a field strength of 20 gauss.

AC power lines are especially good generators of magnetic fields, both low frequency and high frequency radiation caused by corona effects in high voltage transmission lines. A common form of induced noise is found when AC power circuits are placed in close proximity to the instrumentation cabling and the effects of mutual inductance induce 60 cycle noise voltages as larage or larger than the signal on the instrumentation line.

Induction heaters and arcing contacts produce electromagnetic radiation which is high frequency (RF) and modulated by the 60 cycle power frequency and its harmonics. This type of noise is then induced into the instrumentation circuit and demodulated, thus producing spurious noise having the essentials of the 60 cycle power frequency. This type of modulated RF noise can be coupled into the instrumentation lines by conductive, capacitive, and inductive paths.

Solenoids are especially common in an instrumentation test area where fluid valve relays are used in control circuits. These control circuits are usually operated with DC voltages which are switched from one level to another to activate the solenoids. This sudden change in level produces high frequency transients in the coil and the high in-rush of current in the control lines produces a very rapid flux change around the control cable. Other examples of switched DC voltage levels are prevalent in digital logic systems. In these logic circuits the magnetic induction problem is compounded by rapid level transitions, usually several thousand transitions per second.

2.1.3 ELECTROSTATIC RADIATION

From the principles of electrostatics it is given that an object charged with either a negative or a positive charge will remain static until another object carrying the opposite charge is brought close enough to cause a flow of electricity between the two objects. (See Figure 2-3)

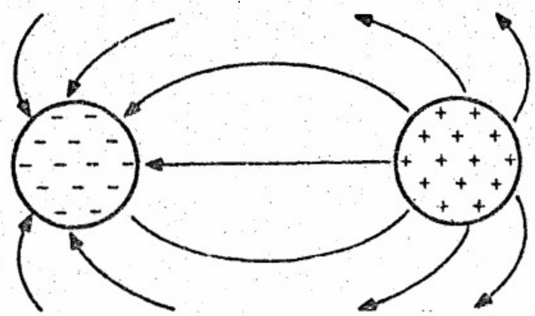


FIGURE 2-3
Electrostatic Radiation

The direction of flow will be from the positively charged object to the negatively charged object.

Quantitatively, the amount of electrostatic noise which will be picked up in a circuit is

$$E_c = j\omega E C_m Z$$

where

E_c = capacitively coupled voltage

$\omega = 2\pi F$

E = source voltage

C_m = mutual capacitance between circuits, inversely proportional to circuit separation

Z = circuit impedance

$j = \sqrt{-1}$

Thus, of primary importance in instrumentation is the distance between source and effected objects because the flow of current between the two objects is inversely related to the distance between them, as well as the impedance of the circuit. Electrostatic induction or radiation is, therefore, caused by the capacitive coupling between the instrumentation circuit and its wiring and the entire surroundings relative to the circuit. This capacitive coupling is entirely

dependent upon the physical configuration, circuit impedance, dielectric between objects, and spacing.

AC, 60 cycle power frequency electrostatic radiation and induction is probably the most common source of noise in any area where low level instrumentation systems are being used. It has been shown in laboratory tests that electrostatically induced voltages can be 8 to 10 times more prominent than those caused by electromagnetic fields under similar conditions.

If the voltage levels in each of two conductors placed in close proximity to each other are different, the potential difference between the conductors is then seen across the coupling capacitance separating the conductors. Thus, if one conductor is carrying a high level AC signal, as for example 60 cycles, this signal can be capacitively coupled into the low level circuit and modulate the signal on that conductor at 60 cycles. Therefore, a practical case exists in an instrumentation system where low level susceptible data transmission cables are routed in the vicinity of and parallel to the power conductor of a single-phase or three-phase power distribution circuit.

Qualitatively, the capacitive coupling, and therefore, the noise increases as the conductors are moved closer together and, for a given configuration and spacing of conductors, noise in the susceptible conductors increases with increasing voltage on the high level power conductors.

Other sources of data acquisition system noise due to electrostatic radiation are electric arcs and corona. The energy radiated by both sources is in the higher frequencies constituting radio frequency rather than power frequency interference.

2.1.4 GROUND CURRENTS

Generally speaking, ground currents can be defined as any current flow in the neutral or common conductor of any circuit, whether it is directly connected to earth or not. If such a current does exist it is very likely to flow back into the circuit which is commonly called a groundloop. The groundloop current can flow back into the circuit by any one or all of the following methods, viz., resistive coupling, capacitive coupling, and electromagnetic induction.

In addition to ground currents associated with an individual circuit, there also may exist considerable earth ground currents which flow below the earth's surface. Earth current is often detrimental to instrumentation systems because of the potentials that exist at different points in the earth. Potential differences between two earth ground rods have been theoretically calculated at well above 10 V peak-to-peak.

To date, a satisfactory method of measurement has not been developed which can be used quantitatively to determine the magnitude in amperes of earth current. Several devices and methods are available which can be used to measure the resistance to earth of a ground electrode with an error of approximately 10%.

However, to measure the amount of stray earth current from one point to another is a very complex matter involving soil resistivity, soil moisture, weather conditions, and depth of electrodes. Because of these factors, readings are taken over a long period of time to obtain average values. Ground currents can be categorized into two general areas:

a. Groundloop current associated with an individual circuit or several circuits.

b. Earth ground currents which flow below the surface of the earth.

Groundloop currents are usually the result of a circuit whose ground points are located indiscriminately throughout a chassis or system. The effects of these groundloop currents are generally familiar to instrumentation users. Further discussion of this subject will, therefore, be avoided except where specifically applicable to instrumentation systems error or noise. More detailed data on ground loops is included in the Bibliography.

Earth ground currents can be caused to flow into an instrumentation system where the transducers are located at remote distances from the acquisition system. The effects of these earth currents in an instrumentation system will be discussed in the next section under common-mode voltages. In this section, many sources of earth currents and how they are distributed in the earth will be discussed.

2.1.4.1 Sources of Earth Ground Currents

The main sources of earth currents are galvanic action, cathodic protection systems, traction systems and electrical power distribution systems.

2.1.4.1.1 Galvanic Action

A current will flow in earth between dissimilar metals which are connected electrically. The action is that which takes place in a battery with the dissimilar metals acting as electrodes, the earth as electrolyte and the electrical connection (usually metallic) as the external, or load circuit. The magnitude of current flow depends upon many factors including:[3]

a. The positions of the two metals in the galvanic series.

b. The total area of dissimilar metals exposed to the soil.

c. The ratio of the exposed area of one of the metals to the exposed area of the other.

d. The chemical constitution and moisture content of the soil.

e. The circuit resistance.

f. Polarization as a result of current flow.

The current flow produced by galvanic action is DC, and while it is a very important agent in corrosion, its contribution to noise is minor.

2.1.4.1.2 Cathodic Protection

A cathodic protection system is sometimes installed at a facility to prevent galvanic corrosion and usually consists of burying a metal which is electrically anodic to the metal being protected and connecting the two to form a galvanic cell as previously described.[3] Under some conditions, an external source, such as a transformer-rectifier unit or motor-generator set is connected between the two metals to assure a controlled flow of current from the anodic metal to the cathodic metal. In either case, the anodic metal is gradually sacrificed to protect the cathodic metal. The current produced is DC and its magnitude depends upon the same factors which affect galvanic action plus the difference of potential of the external source, if applied.

2.1.4.1.3 Traction Systems

Electric trains and streetcars are generally supplied by means of an overhead trolley wire of a "third" rail with the track serving as a current return. No effort is made to insulate the track from earth and the return current flow divides between earth and the rails in inverse proportion to their respective impedance. The current may be AC or DC depending upon the system and its magnitude depends upon several variables including:

a. Earth resistivity.

b. Contact resistance between track and earth.

c. The number, rating and instantaneous tractive effort of all motive units along the line.

2.1.4.1.4 Electrical Power Distribution Systems

A major source of earth currents is power distribution systems. The nature and extent of earth currents associated with a particular power transmission or distribution circuit depends largely upon the types of system, that is, whether the system is grounded or ungrounded; single-phase, three-phase (three wire or three-phase); four wire; whether the load is balanced or unbalanced; transformer connections; and the presence and magnitude of triplen harmonics (third harmonic and odd multiples).

The largest earth currents will flow during a power system fault. However, the faults do not occur frequently and, on most systems, protective devices are designed to clear the fault within a few cycles (at 60 cycles per second) to limit damage to the system. Due to their infrequent and transitory nature, fault currents will not be considered further as a source of data acquisition system noise.

Power system earth currents under normal conditions are considerably smaller than fault currents. Their magnitude may vary from hour to hour but their flow is continuous over relatively long periods of time.

Because of some basic differences in design and operating practices between utility power transmission and distribution systems and test facility power distribution systems, the two will be treated separately.

a. Test Facility Power Distribution - Power to test facility loads is typically distributed at two or three voltage levels:[7]

1. 208/120Y V, three-phase, four wire of 120/240 V single-phase, three wire to small equipment loads, convenience receptacles and some or all of the lighting. The wiring method used is usually insulated conductors in conduit.

2. 277/480Y V, three-phase four wire or 480 V, three-phase three wire to larger loads such as three-phase motors, heaters and, in some cases, fluorescent and mercury vapor lighting. Insulated conductors in conduit or armored cable is generally used to distribute power at this level.

3. 4,160 V or 13,800 V, three-phase where loads and/or distances between loads warrant a higher distribution voltage. At this voltage level, power may be distributed either by means of insulated conductors in conduit, armored cable, or by open conductors on poles.

The neutral or common conductor of the 120/208Y or 120/240 V system respectively must be grounded in order for the system to comply with the National Electrical Code.[8] The neutral of the 277/480Y systems may be grounded and usually are in modern design practice. The neutral of 4,160 and 13,800 V systems may be grounded, and modern fault-protective relay schemes favor grounding. The National Electrical Code directs that each system at a given voltage level, which is to be grounded, shall be connected to earth at one point near the source (usually, a transformer). Also, the National Electrical Code states that no connection between neutral conductors and ground are permitted on the load side of the main service disconnect. All neutral conductors are insulated from ground and, under normal operating conditions, no current will flow except under fault conditions.

b. Utility Power Transmission and Distribution - Utility power lines can be subdivided into two classifications according to application: transmission lines which transmit bulk power from a major power source to a major distribution center or which serve as an intertie between major distribution centers, and primary distribution lines which distribute power to individual users. In both classes, power is usually distributed by means of open conductors on poles or towers although some recent installations in residential areas have featured insulated multi-conductor cables buried in the earth. The reasons for grounding the neutral on either classification of power line are the same, namely, to aid in protective relaying, prevent transient

over voltages due to arcing grounds, and to permit the use of lower insulation levels.[6] However, the practices followed with regard to grounding and consequent flow of earth currents differ somewhat between the two classifications.

1. Transmission lines are generally characterized by high voltage (34 KV and above) and balanced load. The system is almost always grounded at this voltage level for the reasons previously outlined. The system neutral is normally connected to earth at the transformers feeding the transmission line. The path for earth current on this type of line is from line-to-earth through the line-to-ground capacitance and back through earth to the neutral. The magnitude of earth current depends upon the line-to-ground capacitance, the degree of unbalance of the load and between the lines themselves, and the amount of triplen harmonics present. Typical values for 220 KV transmission lines, measured at the transformer neutral, range from 2 to 6 AMPS.

   There are no high voltage DC transmission lines in commercial use in the United States at the present time. Some have been proposed as interties between large power systems and short test lines are under construction. The absence of inductive effects on DC transmission lines makes feasible the use of earth as a current return part and at least two transmission lines in Europe operate in this fashion. Lack of operational data prevents an assessment of possible interference problems with instrumentation systems. Theoretically, the DC earth current would approach high density in the surface layer only in the immediate vicinity of the transmission system ground electrodes. The bulk of the current would go deep into the earth and be carried by the low-resistivity hot-core material rather than the high-resistivity upper layers. Tests and operating experience on a high voltage DC transmission line in Gotland, Sweden seem to bear this out.

2. Primary Distribution Lines range generally in voltages from 2.4 to 25 KV. Single-phase may be taken from the line at random points resulting in varying degrees of unbalance along the line. The majority of the primary distribution lines in this country are three-phase, 4 wire with single-phase loads being connected between a phase conductor and the neutral.[9] However, there is an appreciable use of three-phase, three wire lines, ungrounded, with single-phase loads connected between two of the phase conductors. In the latter configuration, earth currents will flow only under fault conditions. Where the system is three-phases, four wire grounded, utility practice is to ground the neutral conductor at numerous points along the line. The National Electrical Safety Code stipulates that the neutral conductor be connected to earth at least four times for each

mile of line.[10] At each point where the neutral conductor is grounded, the current in the neutral will divide between the conductor and earth in inverse proportion to their respective impedances. The magnitude of earth current at any point along the line will depend upon the degree of load unbalance at that point, amount of triplen harmonics and the impedance of earth.

2.1.4.2 Distribution of Earth Ground Currents

The distribution of current flow in the earth depends upon many variables. The prediction or calculation of earth current magnitude and distribution at any particular time and place is very difficult if not impossible. Mathematical expressions have been developed for both DC and AC currents, assuming such idealized conditions as perfectly homogeneous earth of constant resistivity.[11] Although such conditions are rarely approached in practice, some general observations can be made.

In the case of DC, the distribution of current flow in earth will depend upon only the resistivity of the earth. Assuming homogeneous earth over a large area and depth surrounding two electrodes and a distance between the electrodes, if DC current enters the earth at one electrode and leaves at the other, the current will spread out to a great distance and depth, seeking a path of minimum resistance between the two points.

The distribution of AC current in earth is strongly affected by induction caused by the changing magnetic field, these inductive effects predominate over earth resistivity. The earth currents will distribute themselves so as to minimize the energy in the associated magnetic field. In the case of earth return current beneath an AC power transmission or distribution line, the current will flow in a broad zone on both sides of the line, closely following the routine of the line and will be restricted in both depth and lateral dimensions. The relation between current density and lateral distance from an overhead AC line, assuming homogeneous earth, is a complex Bessel function.[12] The current is a maximum directly beneath the line and falls gradually to zero at the extremities of the zone. In general, the width of the zone through which significant earth current flows on each side of an AC transmission or distribution line varies directly with soil resistivity and inversely with frequency.

The principle variable which makes the actual distribution of earth currents so difficult to predict is soil resistivity. The soil is rarely homogeneous at a particular location. Even where the surface soil is uniform over a large area, the subsoil is usually made up of stratified layers of different soil types with varying

moisture content. The resistivity of a given soil can vary by a factor of 100 to 1 for different values of moisture content and temperature. Thus, the resistivity changes from day to day and season to season.

Another item which can radically alter the distribution of earth currents in an area is buried conductive material (such as pipe or uninsulated cable armor). A long buried conductor can literally collect earth current over a wide area and carry it to distant points.

2.1.4.3 Measurement

Because of the large areas and depths involved and the heterogeneity of the conducting medium, no satisfactory methods have been developed for the direct measurement of stray earth currents or current density at a particular point. The ground currents contributed by a specific source can be measured at the point where the current enters or leaves the earth (at the transformer neutral or generator neutral, for example). The difference of potential between two points on the earth's surface, down to a specified depth, can be measured, giving an indirect indication of the magnitude of earth currents in the area.

2.1.5 COMMON-MODE VOLTAGE

In data acquisition and instrumentation systems where accurate low level data is being obtained and processed, the basic limitation regarding the accuracy of the data being acquired is the amount of noise present in the data. In addition to the desired signal there always exists a certain amount of noise or extraneous information which is totally unrelated to the desired signal and thus undesired because of its effects in masking the measurement signal. Of the many forms in which noise can be found one is of major importance in data acquisition and instrumentation systems. This noise is a result of earth currents and/or other potential differences which are called common-mode voltages.

Common-mode voltages are those voltages which appear on each side of a signal line to a common reference point, normally the systems ground or common point. Common-mode voltage can be caused by magnetic induction, capacitive coupling, and resistive coupling. The most troublesome form of common-mode voltage is caused by resistive coupling between two separate ground points. Because of stray earth potentials, a voltage difference is then established between the two earth or ground points. These earth potentials are primarily of 60 cycle power frequency. The potential differences between these ground points may be referred to as the "Common-Mode Generator."

As shown in Figure 2-4, a low impedance ground loop exists around the loop bdefb. Another loop exists around acdefba. In this second loop, a certain amount of the total loop current will develop an IR drop across the transducer impedance and will appear as a signal voltage at the recording device. This apparent signal is

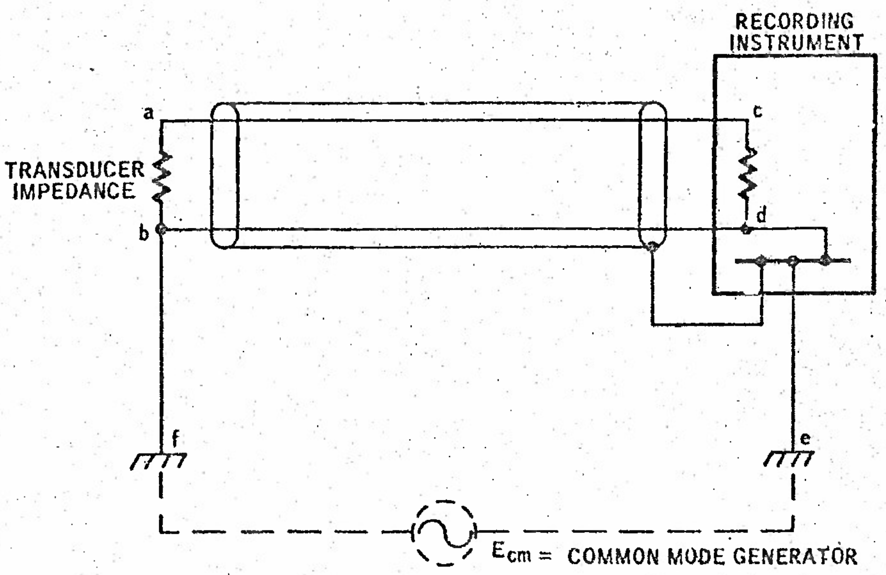


FIGURE 2-4
Common-Mode Generator

the common-mode to normal-mode conversion signal. It is this fact which causes the most concern regarding the accuracy of the data being obtained. Therefore, the less common-mode to normal-mode conversion in the low level transducer and instrumentation cabling the greater will be the overall data accuracy. For more detailed information concerning system accuracies refer to the Appendix.

Common-mode voltage can be divided into three general categories: a) Earth common-mode voltages, b) Transducer common-mode voltages, and c) System common-mode voltages.

2.1.5.1 Earth Common-Mode Voltages

The system shown in Figure 2-5 is a single ended amplifier and recorder type. The system is connected to two different ground potentials, one at the transducer location and one at the recorder. A ground loop consisting of one side of the signal path through the system and the ground itself is formed. The difference in potential between the two ground points, represented in Figure 2-5 by the common-mode voltage generator, causes the flow of ground loop current.

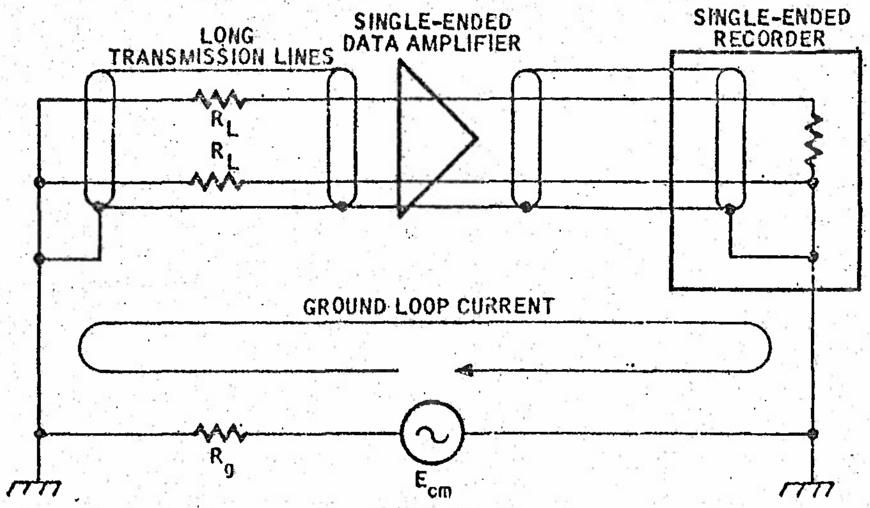
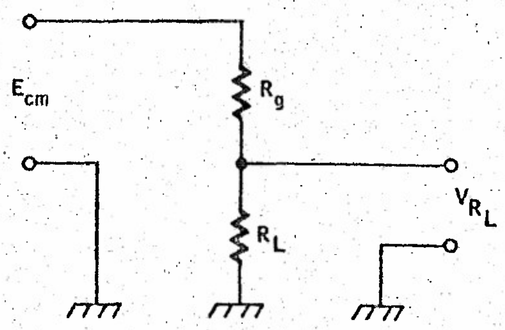


FIGURE 2-5
Typical Simplified Data System Configuration

The flow of current through the transmission line resistance R_L, and the common-mode voltage generator internal impedance R_g



creates a potential difference across R_L equal to

$$V_{R_L} = E_{cm}\left(\frac{R_L}{R_g + R_L}\right)$$

This voltage appears across the input terminals of the amplifier and constitutes a false or erroneous signal to the amplifier and recorder. When working with low-level signals representing the physical measurements, these false signals can completely mask the true information which is to be recorded. A greater error results when the ground loop current is caused to flow through a transducer source impedance which is usually higher than the transmission line resistance.

The grounded transducer is also a typical situation, since it is often not feasible or not economical to isolate transducers from ground. A thermocouple, for example, is generally bonded to the test specimen, forming an almost perfect connection to ground. Imperfect insulation and coupling through stray capacitance are other sources of possible connections to ground.

2.1.5.2 Transducer Common-Mode Voltage

The second type of common-mode voltage, transducer common-mode voltage, frequently occurs as a result of the configuration and type of measuring circuit being used. Figure 2-6 illustrates a typical resistance bridge transducer circuit. Since one side of the excitation power supply is grounded, each of the signal leads going to the data amplifier is placed at a potential of $E_T/2$ above ground. The common-mode voltage appearing at the input of the data amplifier is then $E_T/2$. This would, in most cases, be a DC common-mode voltage. Another source of transducer common-mode voltage will occur between bonded thermocouples because of temperature gradients along the test specimen.

There are other possible transducer circuit configurations and measurements which could result in a common-mode voltage being presented to the input of a data amplifier. Each transducer circuit configuration used in an instrumentation system should be examined carefully to determine the type and level of common-mode voltage that will result.

2.1.5.3 System Common-Mode Voltages

The system common-mode voltage is a result of magnetically induced voltages in the transmission lines from the test area to the instrumentation area. Illustrated in Figure 2-7 is a data system with long cable runs from the test area. Magnetically induced voltages in the cables will occur because of loop areas between the cables, as explained in the above section on magnetic radiation. In a system where several channels are run through conduit to the instrumentation area any separation of instrumentation channels originating from a common area and terminating in an area of close proximity will render the cables susceptable to magnetic fields. Figure 2-7 illustrates a floating data system utilizing the ground bus technique of grounding (discussed in detail later) which has the ground bus separated from the instrumentation cables by a distance D. The amount of induced voltage is

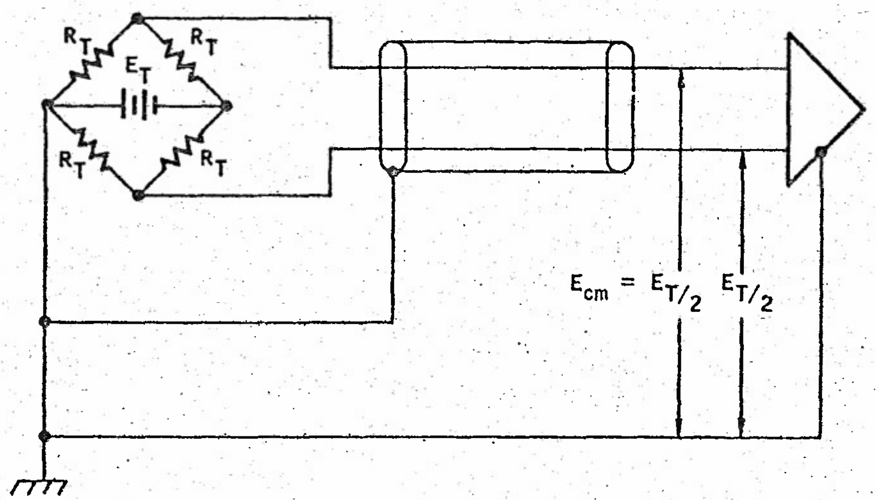


FIGURE 2-6
Typical DC Common-Mode Voltage Source

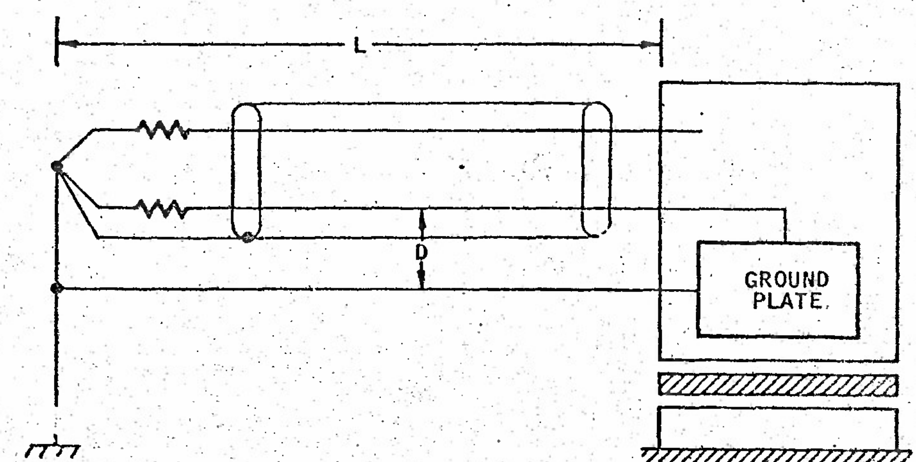


FIGURE 2-7
System With Magnetically Induced Common-Mode Voltages

proportional to the flux density, rate of change of flux, and circuit area. Therefore, the larger the area the more susceptable the instrumentation cables will be to magnetically induced common-mode signals.

2.1.6 OTHER NOISE SOURCES

In the preceding paragraphs, the following noise sources have been discussed: (a) power and transmission systems, (b) electromagnetic radiation, (c) electrostatic radiation, (d) ground currents, and (e) common-mode voltages. In this section noise sources will be discussed which are important and often a very real problem in a rocket test facility utilizing low level DC data acquisition systems. Each of these sources of noise deserves special attention. The effects they have on acquisition accuracies cannot be over emphasized. These noise sources can be categorized as:

a. Thermoelectric emf's

b. Electrochemical emf's

c. Acoustical

d. Cable noise

e. Component noise

f. Sub-system noise

2.1.6.1 Thermoelectric emf's

Instrumentation systems frequently utilize a thermocouple that is welded to the test specimen which is dissimilar to the thermocouple metals themselves. At this junction a thermoelectric potential arises (see Figure 2-8).

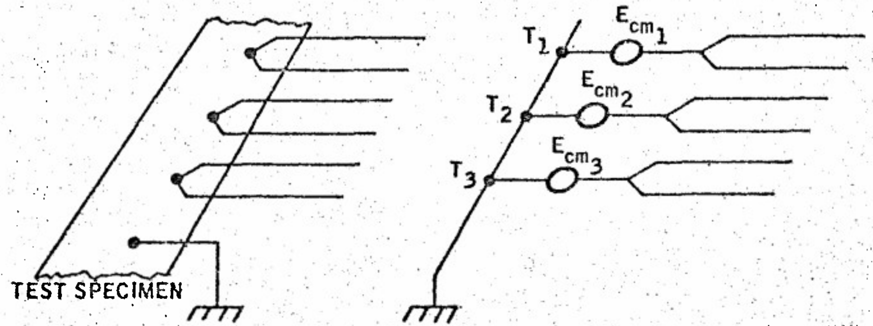


FIGURE 2-8
Bonded Thermocouples

This voltage is a DC common-mode voltage and will be different at each thermocouple if a temperature gradient exists along the test specimen and it will change with temperature. This same effect is possible with signal or ground wire connections which are made of dissimilar metals. As long as perfect symmetry exists on both sides of the couple and for the length of the thermocouple lines, any temperature gradients along the length of the thermocouple leads cause no problems, since junction emf's will cancel.

If there is a temperature difference between point 1 and 2 (see Figure 2-9), this causes common-mode to normal-mode conversion error. For example, at the copper-constantan junction a 1°C difference between points 1 and 2 will produce 40 MV of DC signal.[12] Therefore it can be seen that in a rocket test start where there are rapid changes in temperature, large temperature gradients are not uncommon.

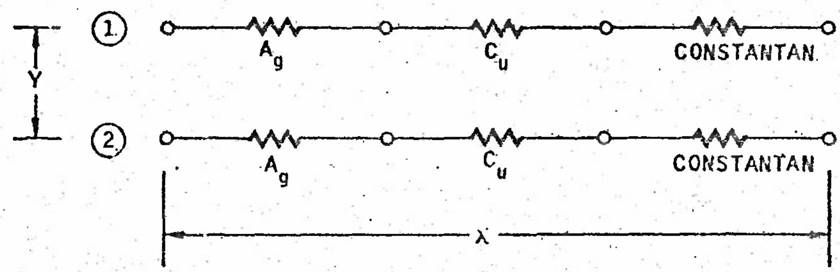


FIGURE 2-9

Two Thermocouples with a Temperature Gradient between Points 1 and 2

2.1.6.2 Electrochemical emf's

Chemicals have been known to cause noise in instrumentation systems under certain conditions. Chemicals can form noise voltages through the voltic action of electrolyte type chemicals. Nitric acid spilled on the floor of a rocket engine test stand has been known to generate a significant emf in the earth ground path.[13]

2.1.6.3 Acoustical

Acoustical environments greater than 120 db are, in certain cases, another source of instrumentation noise and can introduce error into the data measurement. Gage-type pressure transducers whose transduction element depends on convection cooling should be avoided in a high acoustic environment. Zero balance can be altered significantly by thermodynamic changes caused by the acoustic background.[12]

2.1.6.4 Cable Noise

Cable noise can be observed in especially high impedance instrumentation circuits when the cable is subjected to mechanical distortions such as bending, tapping, and squeezing. Figure 2-10 shows an oscilliogram taken of a length of foil shielded cable in a very high impedance circuit which was taped twice in opposite directions. It is clear then that there exists charges between the cable insulation and the conductors and between the insulation and the shield.

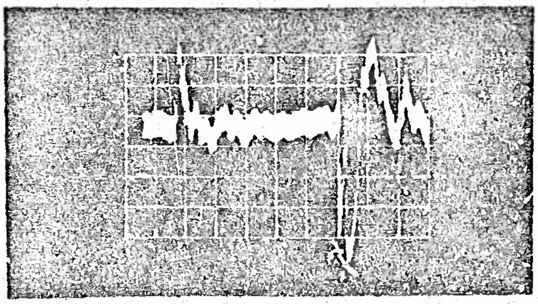


FIGURE 2-10
Cable Noise in High Impedance Circuit

This type of noise is called Triboelectric Cable Noise. It is a result of the separation of triboelectric charges when the dielectric momentarily looses intimate contact with either the center conductor or the shield because of mechanical distortion[14] (see Figure 2-11).

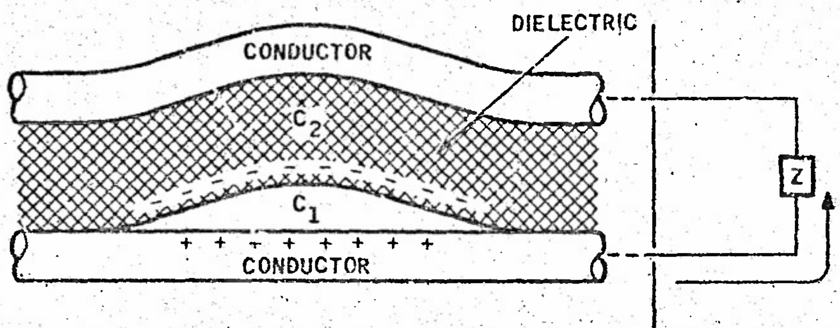


FIGURE 2-11
Triboelectric Cable Noise

2.1.6.5 Component Noise

Composition resistors, semiconductors, and electrolytic capacitors are examples of components which are sources of noise if their characteristics are not adequately considered and the components carefully us i. Electrolytic capacitors, for example, have been known to produce an electrochemical DC offset voltage in a low-pass filter at the input to a high gain servo amplifier.

Resistor noise is common and is generally the result of thermally agitated electrons within the resistance itself. The thermal noise level generated by a resistance is called "Johnson Noise" and expressed as follows:

$$Vn = \sqrt{4kTBRg}$$

$$= 2\sqrt{1.38X10^{-23}TRgB}$$

Where: B = Bandwidth

T = Temperature in degrees Kelvin

Rg = Resistance of component

k = Boltzman's Contant = $1.38X10^{-23}$ Meter-Kilogram-Second

At any given temperature, any resistance or resistive component generates random wideband noise due to thermal agitation of electrons. The noise power generated is proportional to the resistance, temperature, and bandwidth of the circuit.

Semiconductor noise is wideband and caused by electrons crossing any semiconductor "barrier". This noise is proportional to current and to the circuit bandwidth. Therefore, in low bandwidth low current instrumentation systems this form of noise may be of significant magnitude

Solder connections can also generate thermal emf's. Regular tin-lead solder has a high thermal emf relationship to copper. A low thermal solder 70% cadmium and 30% tin is available for low level circuits which can give better than a 100 to 1 thermal emf reduction.

Contact noise can be a very serious problem in space environmental test chambers, and rocket test areas where metal corrosion is caused by toxic fuels being discharged from the test specimen. Contacts such as terminal strip connectors, relay and switch contacts can exhibit noise where there are fluctuations of conductivity at an imperfect junction between the two conductors. Two important factors influence the amount of noise generated by imperfect contacts: (1) the noise is directly proportional to the DC current through the contact; and (2) the power density plotted on a frequency scale varies inversely with frequency so that in a given DC current the noise power increases with decreasing frequency.[15]

2.1.6.6 Subsystem Noise

Instrumentation amplifiers have inherent noise within the circuits of the amplifier. This noise as almost always given in the amplifier performance specification refers to full scale input signal, bandwidth, gain, and source impedance. Modern instrumentation amplifiers have low noise levels which approach the theoretical limits of the "Johnson Noise" described above.

Power supplies with poor regulation produce ripple voltages which can be carried directly to the input to the instrumentation system. Regulation elements in power supplies such as silicon-controlled-rectifiers are a particular problem when used in some digital systems. The switching transients of the rectifier may be present on the AC power line and carried to susceptable circuits whose power is supplied by this same AC line. If the power supply cannot regulate such fast transients, then they appear as spikes on the DC voltage output causing random triggering of logic circuits.

2.1.7 TRANSMISSION LINES

Data transmission lines operating at low voltage levels and more importantly at low frequencies, have electrical characteristics that require a differential analysis than those of high frequency transmission cables. At low frequency, cable capacitance and line resistance are of primary interest concerning the noise contribution and noise susceptibility of low frequency data transmission cables.

High frequency signals such as the output of piezoelectric type accelerometer or vibration pick-ups are usually the highest frequencies used in analog instrumentation systems. The range of such transducers is commonly 4000 to 6000 CPS. In instrumentation systems the length of a transmission cable will rarely be more than a small fraction of the wavelength of the highest data frequency; therefore transmission line theory related to wavelengths of frequency are not generally applicable.

At frequencies below 1000 CPS the shunt resistance and series inductance of a cable is quite small when compared with the series resistance and shunt capacitance of a cable at higher frequencies. Thus, at low frequencies shunt resistance and series inductance may be neglected. The transmission line then appears basically as a shunt capacitance when open circuited, and the termination impedance is in series with the line resistance and in parallel with the line capacitance when terminated. Figure 2-12A shows the equivalent cable with distributed constants while Figure 2-12B shows the lumped constants configuration of the same cable.

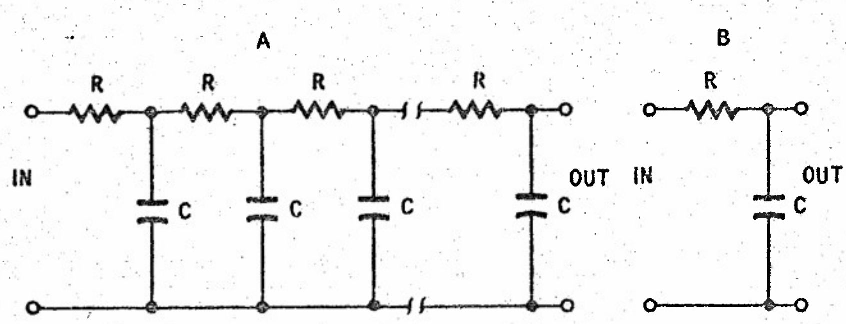


FIGURE 2-12

Approximate Equivalent Circuit for Low Frequency Cables

It should be noted that at the lower frequencies the characteristic impedances of transmission lines are of no significance as rarely will the line be as long as one-quarter wavelength of the highest instrument frequency. Typical values of wire resistance and cable capacitance for coaxial cables and a typical 22 gage parallel wire cable are given in Table 2-1 below.

Cable	Ohms/Foot	Picofarads/Foot
RG58C/U	.01	28.5 (wire-to-shield)
22 gage pair*	.032	13 (wire-to-wire)

*Spacing = 4X radius and dielectric constant = 2, no shield considered. Resistance 2X single length.

TABLE 2-1

Typical Values of Wire Resistance and Cable Capacitance for Coaxial Cables

The capacitance per foot for coaxial and parallel wires may be found by use of the following formulas and by referring to Appendix B. Coaxial cable specifications are also found in engineering handbooks.

a. Coaxial Cable Capacitance

$$\frac{7.94\ K \times 10^{-12}}{\text{Log } 10 \ \ b/a} \quad \text{farads per foot of line}$$

where

a = Radius of outer surface of inner wire

b = Radius of inner surface of outer conductor

k = Relative dielectric constant of inner insulation (K = 1 for air)

b. Parallel Line Capacitance*

$$\frac{4K\ 10^{-12}}{\text{Log } 10\ b/a} \quad \text{farads per foot of line}$$

where

a = radius of each wire

b = Spacing between wire centers

k = Relative dielectric constant of insulation

*Twisted lines would have a larger capacitance.

A typical transducer with a given cable shunt capacitance C_c and se[r]ies resistance R_c and a resistive load R_L may be approximated by the circuit shown in Figure 2-13. The signal source may be either a transducer or the output of a line amplifier with an impedance Z_s.

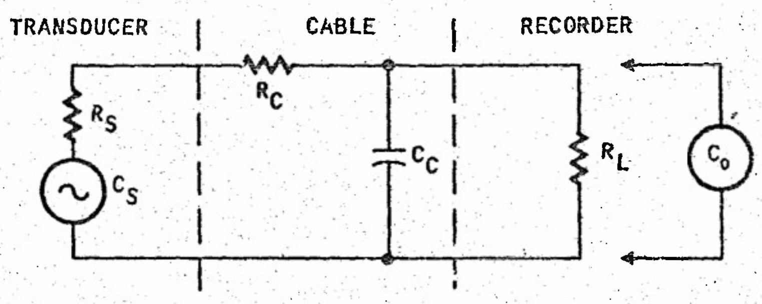


FIGURE 2-13

Approximate Equivalent Circuit for Low Frequency Transducer and Lumped Constants Cable

The output voltage e_o would be a product of the voltage divider as shown in Figure 2-14.

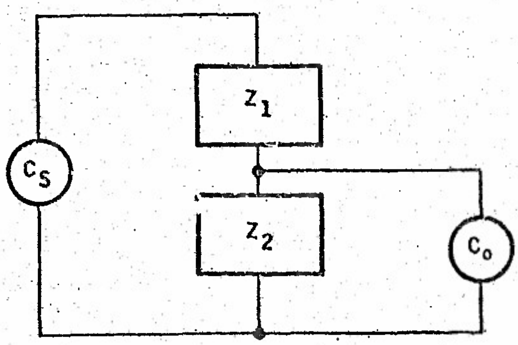


FIGURE 2-14
Simplified Equivalent Circuit of Low Frequency Transducer Cable with Lumped Constants

and the output e_o relative to e_s is:

$$\frac{e_o}{e_s} = \frac{Z_2}{Z_1 \quad Z_2}$$

where $Z_1 = R_s + R_c$

$Z_2 = R_L$ parallel with C_c

As the impedance of C_c is normally much less than the input impedance of a given recorder R_c, then R_L may be dropped and the output e_o referenced to e_s is now

$$\frac{e_o}{e_s} = \frac{jX_c}{R_s + R_c - jXc} = \frac{1}{1 + j\,(R_s + R_c)\,(2\pi FC)}$$

where F is the frequency of the output of the transducer.

It can be seen that at higher frequencies and with long lines there would be an error due to the line shunt capacitance. As an example, 500 feet of RG58 cable, a transducer with a 4000 CPS range, and a source impedance of 1000 ohms would produce a signal error (amplitude attenuation) of almost 7% at the high frequency. As an indication of the importance of low source impedances if R_1 were 100 ohms the signal error would be about .07%.

At lower frequencies or where R_c is quite small the output relative to the input is:

$$\frac{e_o}{e_s} = \frac{R_c}{R_1 \quad R_c \quad R_c}$$

From the above relationship it can be seen that if the line resistance is within a reasonable percentage of the load impedance, as it would be if an oscillograph galvanometer were driven directly from a transducer, the line resistance would cause an error. Usually DC errors which are fixed in nature such as the line resistance can usually be compensated for during calibration.

Transmission lines which are located in severe environments will be subjected to extreme temperature variations. This can cause thermal EMF in cables which are nonhomogenious (e.g., wire with varying alloy throughout its length, rare with copper wire, but possible in thermocouple wire) and changes in resistance present in all wires to varying degrees. A simplified relationship for changes of resistance in wire is:

$$R = R_0 \; (1 + X_t)$$

where R_0 is the relative resistance at $0^{\circ}C$, X is the temperature coefficient and t is in degrees centigrade.

If R_0 is normalized to one the coefficient X for copper is .00393. Temperature coefficient for many materials may be found in the "Handbook of Chemistry and Physics". The result is that a $10^{\circ}C$ change in temperature can change the resistance of a copper wire by approximately 4% or 1.3 ohms in a double run of 1000 feet of 22 gage wire. If used in the balanced bridge circuit of Figure 2-15, the output error would be 21 MV, a large error in a low level system.

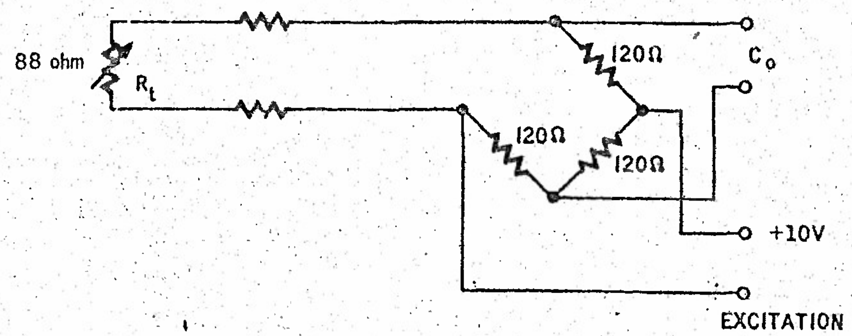


FIGURE 2-15
Remotely Located Single Active Element Bridge

2.2 NOISE REDUCTION AND PREVENTION

2.2.1 GROUNDING

Grounding is a general term used to describe that part of a circuit, system, or power equipment which is a common voltage reference point or datum from which the operating voltages of the circuit, system, or power equipment may be measured. This zero voltage reference point is not necessarily connected to earth ground. A connection to earth ground is used, however, for two important reasons: (1) to fix the common or neutral point of an electrical system to earth potential which is theoretically at zero volts; and (2) to provide a low impedance current path to earth (zero volts) for the safety and protection of personnel. When an electrical failure occurs in an electrical power system, very large amounts of current can be passed into conduit, motor cases, junction enclosures, etc. If these devices are grounded at earth potential through low impedance connections (25 ohms or less) no harm to personnel will occur during an electrical fault condition.

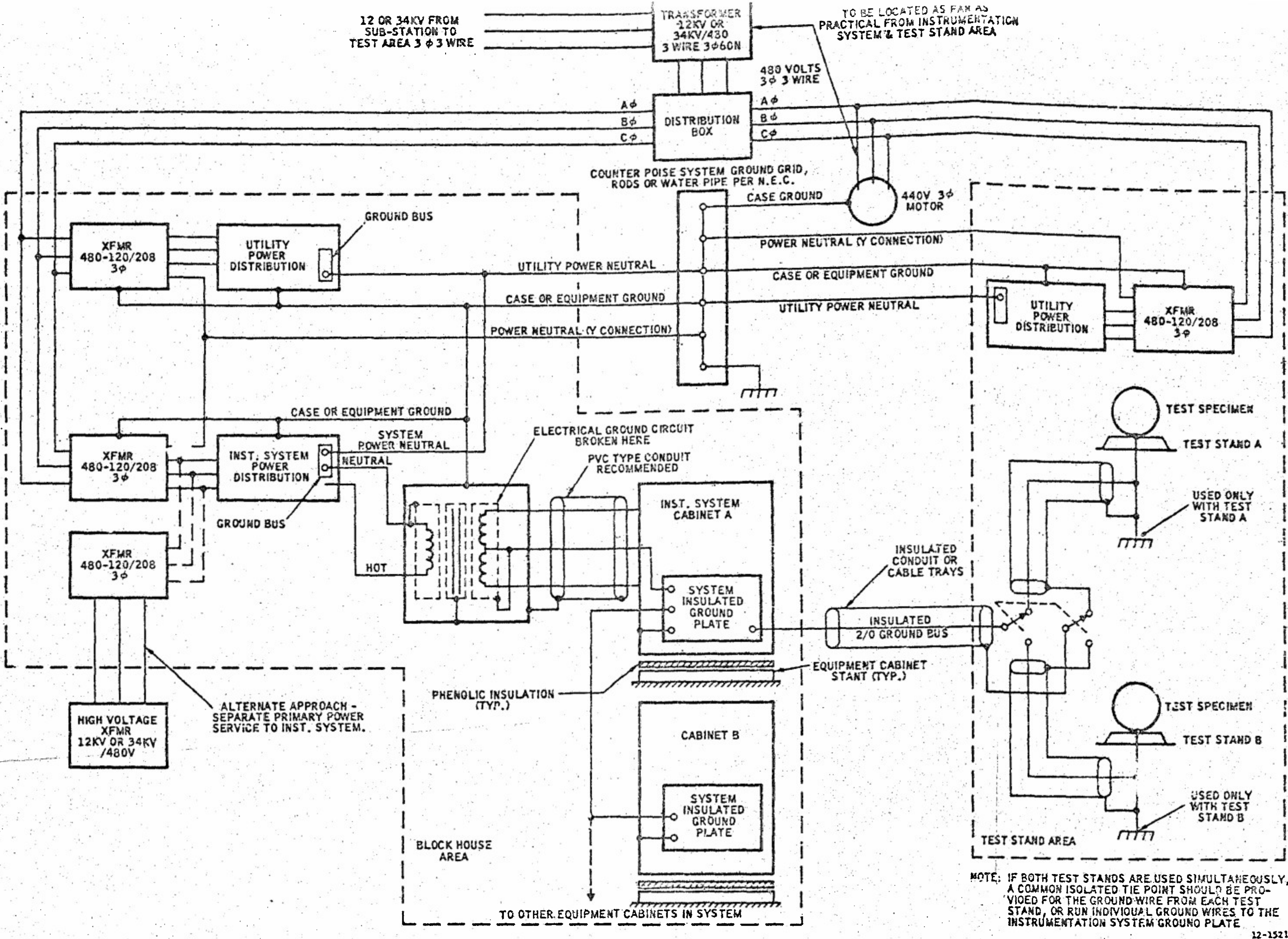
In an overall grounding system design for a low-level instrumentation test facility, there are two categories of ground systems which must be considered. First, the electrical power grounding system which includes all AC power, both distribution and utility service power used for lighting, equipment power, etc. Second, signal circuit grounding which includes all electronic and electrical control circuits associated with the instrumentation equipment. The design of each of these grounding systems for an instrumentation facility must include careful consideration - both independently and with respect to each other.

2.2.1.1 Power Grounds

As previously explained, earth currents are always present in an area where heavy electrical equipment is being used. Therefore, it is important to minimize the amount of high-power electrical equipment in the area of the instrumentation equipment.

In Figure 2-16, primary power circuits and grounding techniques are those which are standard and required by the National Electrical Code. The most important consideration concerning the primary power system is that of its relative location to the instrumentation system; all heavy electrical equipment and primary power distribution should be placed as far as possible from the instrumentation system so that power caused earth currents will be decreased through the resistance of the earth. As shown in Figure 2-17, one half mile is recommended as minimum separation between blockhouse and power transmission line. This distance is based on the need to reduce earth current and radiation effects to negligible values yet maintain a reasonable proximity between the instrumentation complex and power source.

Earth currents associated with high voltage transmission lines and earth currents which have been "trapped" by buried conduit follow the direction of the transmission lines and conduit. It is therefore recommended that a perpendicular relationship



12 OR 34KV FROM SUB-STATION TO TEST AREA 3 φ 3 WIRE
TRANSFORMER 12KV OR 34KV/430 3 WIRE 3φ60N
TO BE LOCATED AS FAR AS PRACTICAL FROM INSTRUMENTATION SYSTEM & TEST STAND AREA
480 VOLTS 3φ 3 WIRE
Aφ
Bφ
Cφ
DISTRIBUTION BOX
COUNTER POISE SYSTEM GROUND GRID, RODS OR WATER PIPE PER N.E.C.
CASE GROUND
440V 3φ MOTOR
GROUND BUS
XFMR 480-120/208 3φ
UTILITY POWER DISTRIBUTION
UTILITY POWER NEUTRAL
CASE OR EQUIPMENT GROUND
POWER NEUTRAL (Y CONNECTION)
CASE OR EQUIPMENT GROUND
UTILITY POWER NEUTRAL
POWER NEUTRAL (Y CONNECTION)
UTILITY POWER DISTRIBUTION
XFMR 480-120/208 3φ
CASE OR EQUIPMENT GROUND
SYSTEM POWER NEUTRAL
NEUTRAL
XFMR 480-120/208 3φ
INST. SYSTEM POWER DISTRIBUTION
GROUND BUS
ELECTRICAL GROUND CIRCUIT BROKEN HERE
PVC TYPE CONDUIT RECOMMENDED
INST. SYSTEM CABINET A
TEST SPECIMEN
TEST STAND A
USED ONLY WITH TEST STAND A
XFMR 480-120/208 3φ
HOT
SYSTEM INSULATED GROUND PLATE
INSULATED CONDUIT OR CABLE TRAYS
INSULATED 2/0 GROUND BUS
HIGH VOLTAGE XFMR 12KV OR 34KV /480V
ALTERNATE APPROACH - SEPARATE PRIMARY POWER SERVICE TO INST. SYSTEM.
PHENOLIC INSULATION (TYP.)
EQUIPMENT CABINET STANT (TYP.)
CABINET B
SYSTEM INSULATED GROUND PLATE
TEST SPECIMEN
TEST STAND B
USED ONLY WITH TEST STAND B
BLOCK HOUSE AREA
TEST STAND AREA
TO OTHER EQUIPMENT CABINETS IN SYSTEM
NOTE: IF BOTH TEST STANDS ARE USED SIMULTANEOUSLY, A COMMON ISOLATED TIE POINT SHOULD BE PROVIDED FOR THE GROUND WIRE FROM EACH TEST STAND, OR RUN INDIVIDUAL GROUND WIRES TO THE INSTRUMENTATION SYSTEM GROUND PLATE
12-1521

FIGURE 2-16

be maintained between test area-to-blockhouse cable runs, and any power lines which are carried through the area. Also, instrumentation conduit should never pass under or parallel to such power transmission lines.

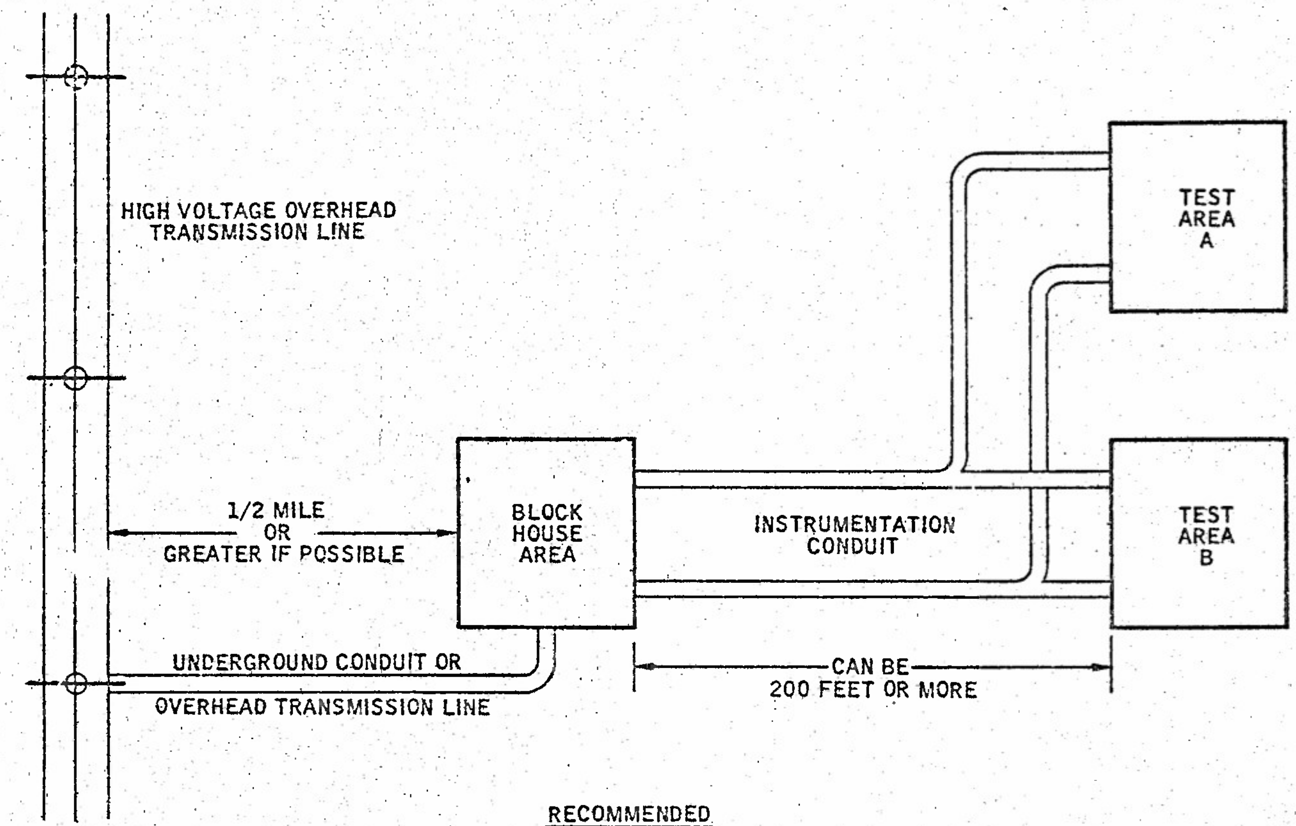
Inside the instrumentation test facility the electrical grounding of power circuits and equipment should follow closely the requirements of the National Electrical Code. However, the the grounding of the low-level low-frequency instrumentation equipment cabinets should be separate from the standard AC power equipment point from the AC power circuits, AC ground currents will be eliminated in the cabinets, thus eliminating instrumentation noise associated with the pickup of 60 cycle potentials in the cabinet itself. (Equipment cabinet isolation is covered in more detail in Paragraph 2.2.4.) Figure 2-16 shows a power system grounding design which will eliminate or greatly reduce any noise or ground currents in the instrumentation system. The principles in this design are as follows:

a. Power circuits provided with adequate ground return to earth as required by National Electrical Code.

b. Isolation transformers should be used to supply Instrumentation system power to prevent ground loops between electrical power ground points and instrumentation ground point.

There have been many articles written on the subject of electrical power system grounding. Some of these articles give rigorous explanations concerning the design requirements of an electrical grounding system. One such article, entitled "The Realization of Compatible Structure Grounding Systems" by H. W. Ervin, D. R. Lightner, and Robert Powers, gives a design criteria of a ground system for both electrical and electronic facilities where high frequency RF electromagnetic fields are present or generated. Although the scope of this Handbook does not include high frequency type systems such as radar stations and facilities, it is important to note that because of the electromagnetic radiation problems associated with such systems the grounding requirements are significantly different from those used in low-frequency low-level instrumentation. The grounding of a high frequency system should consist of many unconnected parallel paths originating at the circuits, modules or subsystems (See Figure 2-18) and terminating at a common ground point so that the ground currents can be distributed to the ground point through as low an impedance path as possible and through the shortest path as possible. Figure 2-19 illustrates how the current in an isolated conductor is distributed when the current is at radio frequencies.

As the frequency being transmitted by the wire increases, the inductance and impedance in the center of the wire increases greatly to where the current in this area is effected and caused to flow at the surface of the conductor. The useful current carrying area of the conductor is reduced and the effective impedance of the conducer is increased. Therefore, when grounding high frequency circuits, many



RECOMMENDED

FIGURE 2-17
Recommended Power and Instrumentation Facility Orientation and Conduit Usage

ground paths to earth effectively lowers the impedance offered to the current as well as divides the total current between the conductors.

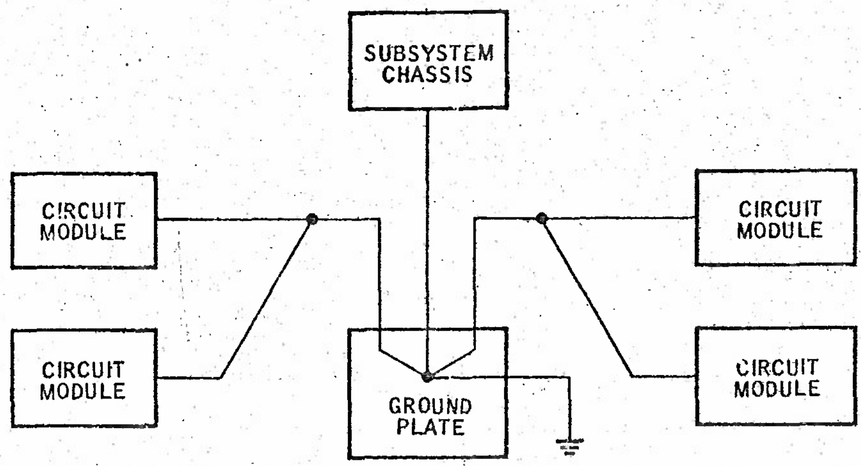


FIGURE 2-18
Simplified Diagram of Multiple Ground Paths

In contrast, a low-frequency instrumentation system measuring data from 1 to 5000 CPS requires that each ground circuit be maintained ungrounded until it reaches the system ground point. This is done to eliminate ground loops which are susceptible to error causing ground currents and to magnetically induced error voltages.

2.2.1.2 Signal Circuit Grounds

The "signal ground" is associated with the transmission of data or control signals. The signal ground circuit is therefore a separate entity and is distinguished from the electrical power ground or AC return and the equipment ground which is required by the National Electrical Code for human safety and protection against electrical faults.

In data instrumentation there are two forms of signal grounds. Each one is associated with the function of signal transmission in the system such as acquisition, reduction, and conversion of low-level voltage measurements to engineering units. These signal grounds are analog signal grounds and digital signal grounds.

2.2.1.2.1 Analog Signal Grounds

Analog signal grounds in an instrumentation system are those grounds associated with the analog voltage circuits such as transducers, and relay and solenoid control circuits. Transducer is a general term which describes any device that con-

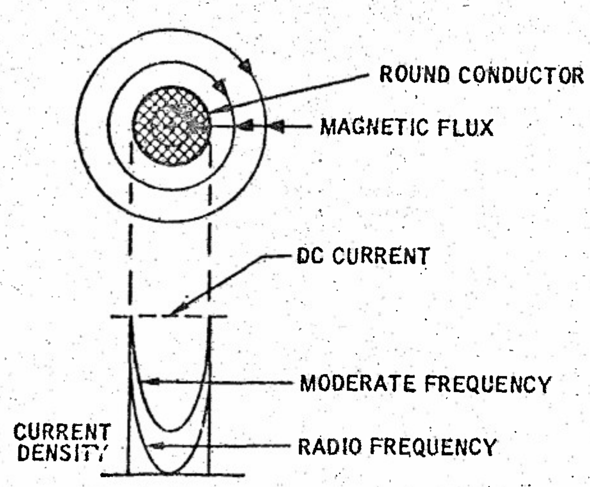


FIGURE 2-19

Isolated Round Conductor Showing Magnetic Flux Paths and Typical Current Distributions

verts energy of one form into energy of another form, such as a motor generator which converts the energy of mechanical rotation into electrical energy.

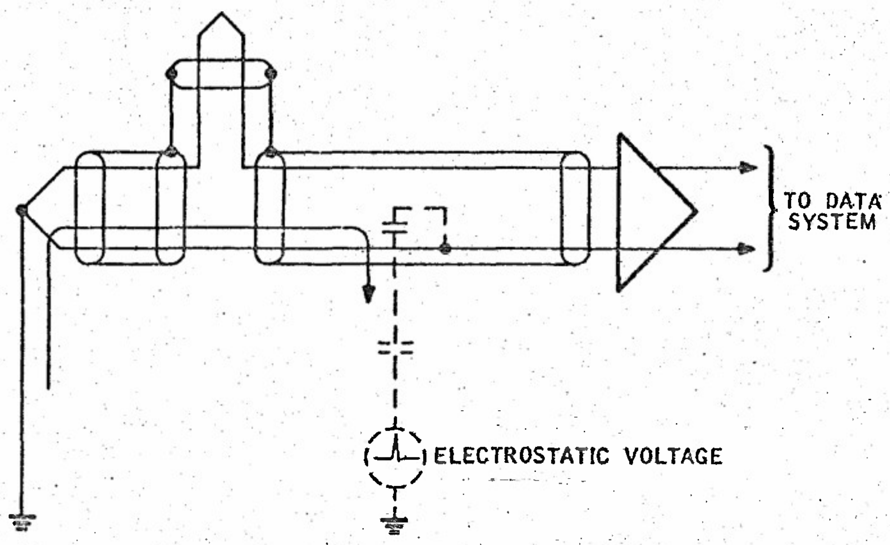
Analog signal grounds must be considered in relation to the signal producing transducer and to the signal amplifier as well. Amplifiers may be classed into two types: single-ended and differential (isolated, feedback).

Other important analog signal grounding considerations include prevention of ground loops by more than one common ground point in the analog signal section and the grounding methods which should be used in a multiple test stand facility.

The grounding procedures given will be for transducers in general since the grounding techniques discussed will apply to almost all transducers in common use today in a rocket test facility and instrumentation system. When considering measurements, there are two choices which can be made: (1) use a grounded transducer such as a bonded thermocouple or; (2) use an ungrounded transducer such as a strain gage bridge transducer. In each type of transducer the maximum measurement accuracy can be obtained only if noise is reduced in the measurement. By properly grounding each transducer type, many of the deterrents in obtaining higher data accuracies can be eliminated.

a. Grounded Transducers - Figures 2-20 and 2-21 are bonded thermocouple transducers which are commonly used in instrumentation systems. The thermocouple is shown utilized in two system configurations. In the first

configuration, Figure 2-20, a thermocouple is used with a single-ended data amplifier whose output is taken into the data system to drive recording devices such as oscilloraphs, strip-chart recorders, etc. The shield which surrounds the transducer signal leads must be grounded to pass any electrostatically induced currents directly to earth. If the shield is not grounded the strong possibility exists that these currents will flow directly through the signal leads via shield-to-signal-lead capacitance.



NOT RECOMMENDED

FIGURE 2-20
Shield Current Flow Through Signal Leads
When Shield Not Grounded

It is therefore natural to question which end of the shield should be grounded to allow shield currents to flow directly to earth. The best place to ground the shield is at the same point which grounds the transducer. This insures that shield and signal leads are always at virtually the same potential. This recommended practice is illustrated in Figure 2-21.

Grounding of the shield at the amplifier end of grounded transducer signal lines can cause extremely high common-mode noise as shown in Figure 2-22. The large capacitance between shield and signal lines (typically 50 pf/ foot) is a relatively low impedance path for AC currents caused by common-mode voltages (E_{cm}). As can be seen, the E_{cm} current path includes the

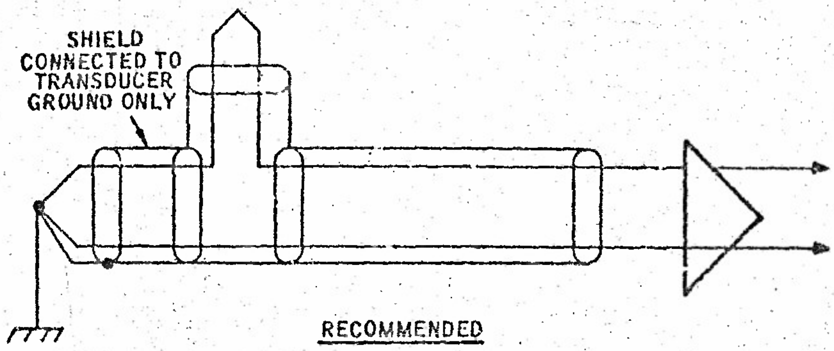


FIGURE 2-21
Shield Should be Grounded at Grounding Point of Transducer

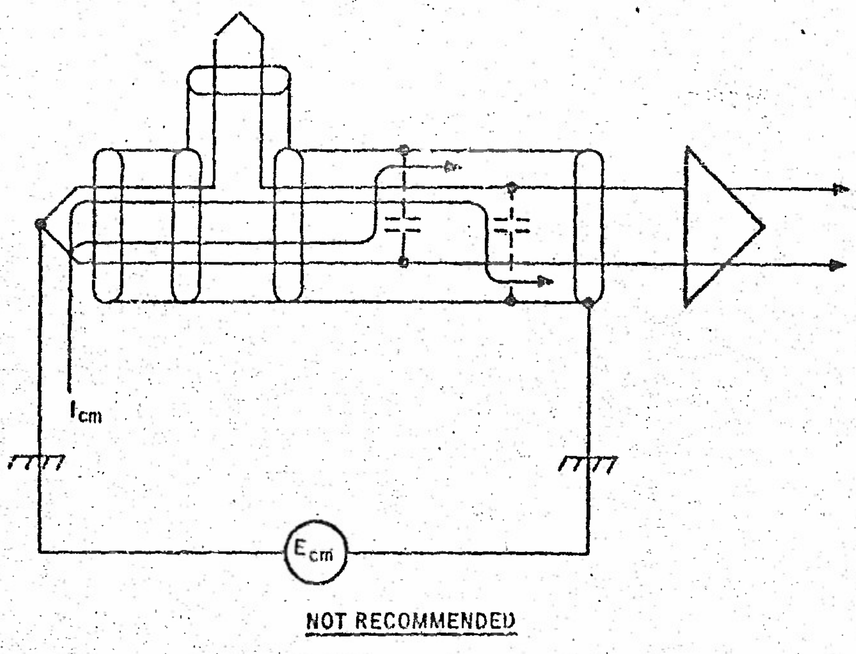


FIGURE 2-22
Shield Should Not be Grounded at Opposite End of Signal Lines From Transducer

signal lines themselves. This means that common-mode noise voltages will be developed in the signal lines in direct proportion to the amount of line resistance and the amount of common-mode current generated.

As shown in Figure 2-23, common-mode currents are virtually eliminated by connecting both shield and transducer to the same ground point.

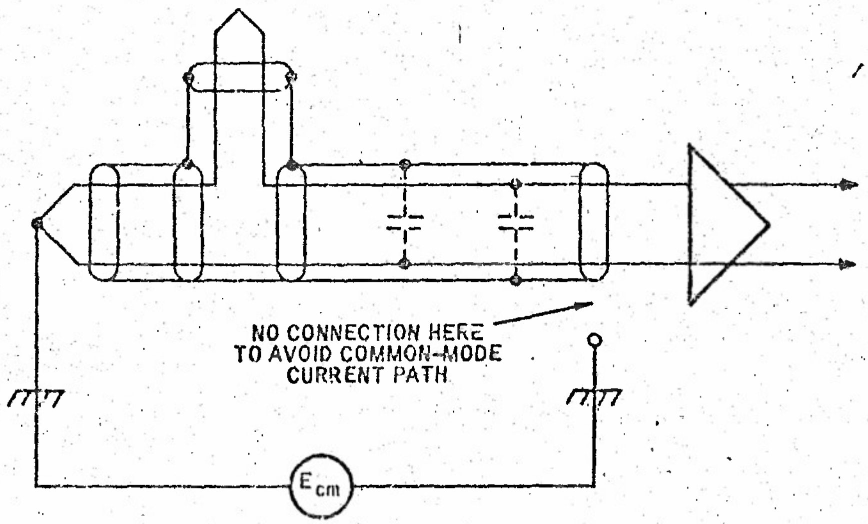


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FIGURE 2-23

Common-Mode Current Path Eliminated

In Figure 2-24, a bonded thermocouple is connected to the input of an isolated DC amplifier. The shield of the input cable to the amplifier is connected to the amplifier internal guard shield which serves as an extension of the signal shield within the amplifier. In addition, a ground line is shown connected between the data system ground point and earth ground of the test area. This ground bus is necessary in any instrumentation system which uses isolated differential amplifiers for two reasons:

1. It serves as the earth reference for the recording system to reduce high voltage hazards.
2. It practically eliminates common-mode potentials which would otherwise exist between amplifier input and output if the data system were totally earth grounded.

Note that the amplifier case and output shield is grounded at data system grounding plate. This grounding technique, and that shown for the signal

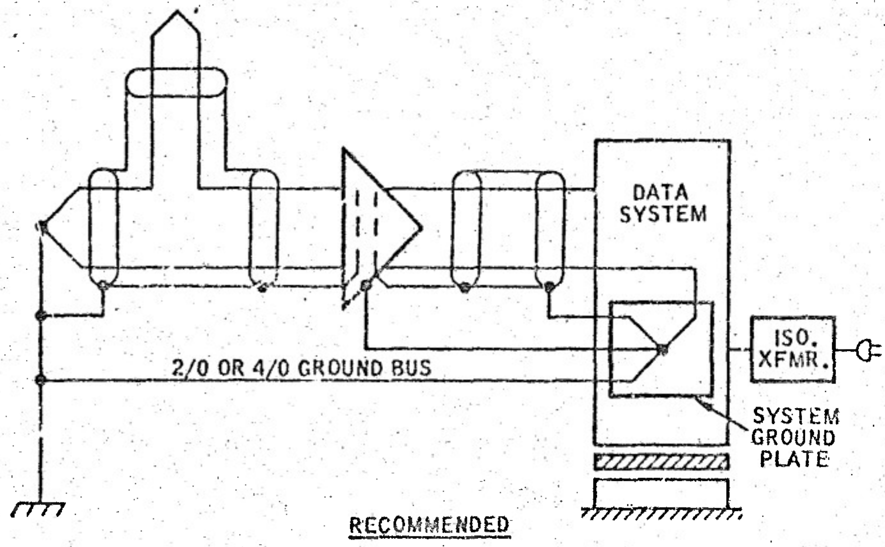


FIGURE 2-24

Differential Amplifier With a Bonded Transducer Input. Guard Shield Connected to Ground at Transducer Ground Point

input conforms to one significant grounding principle; the elimination of noise susceptable loops.

If grounded bridge circuits are being instrumented, careful consideration should be given to the manner in which they will be used. Figure 2-25 illustrates a single channel grounded bridge transducer with DC excitation and a single-ended amplifier.

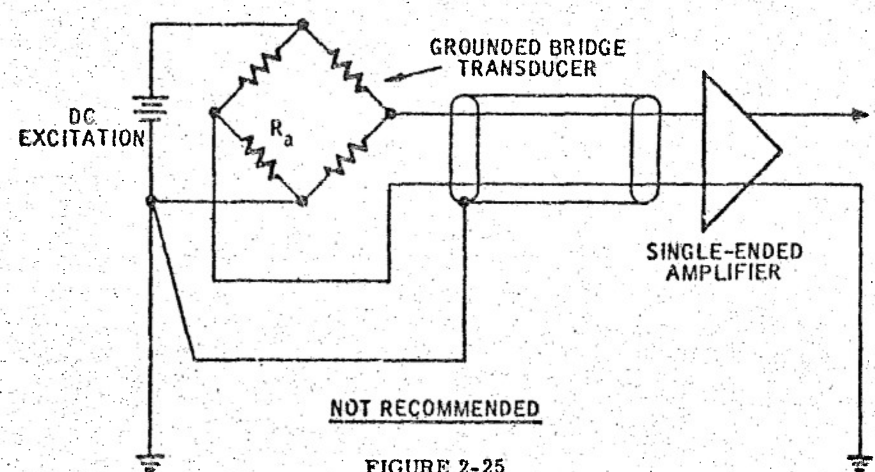


FIGURE 2-25

Single Channel Grounded Bridge Transducer

The resistor R_a can be shorted out entirely in this method of grounding, thus destroying the characteristics of the bridge. By balancing the DC excitation supply to ground, as shown in Figure 2-26, the entire bridge will then be balanced with respect to earth and the unbalanced impedance presented to the amplifier input will be due only to the leg resistances in the bridge.

Although a ground loop still exists its effect will be greatly reduced by a balanced excitation supply to earth.

A significant movement over the above circuits can be achieved if an isolated amplifier is used as illustrated in Figure 2-27. In this configuration, two grounds can exist between the grounded transducer and amplifier without degrading system performance since essentially no earth common-mode generator exists between the two areas.

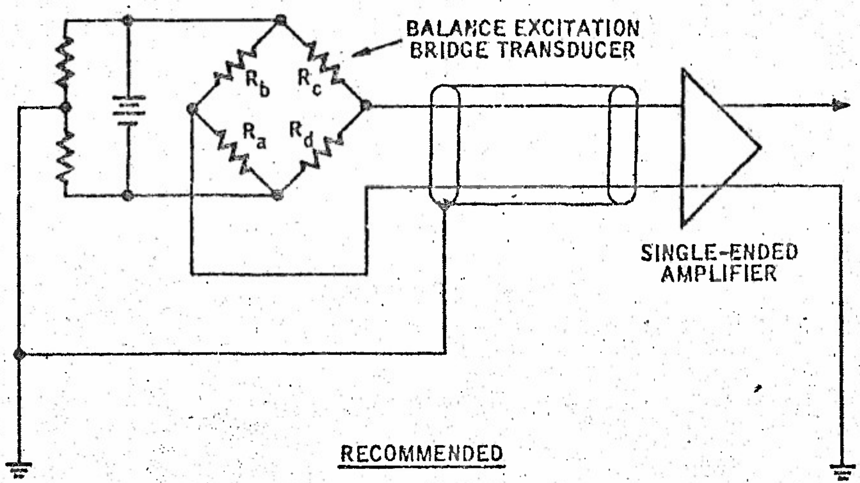


FIGURE 2-26
Balanced Method of Grounded Bridge Circuit

Some recommended practices for use with grounded transducers are given below:

1. Ground shield and transducer at same point where possible.
2. Connect guard shield of amplifier input to shield of signal cable.
3. Use two conductor shielded cable where possible, (e.g. thermocouple extension wires).
4. Connect amplifier output shield and low side to data system ground block.

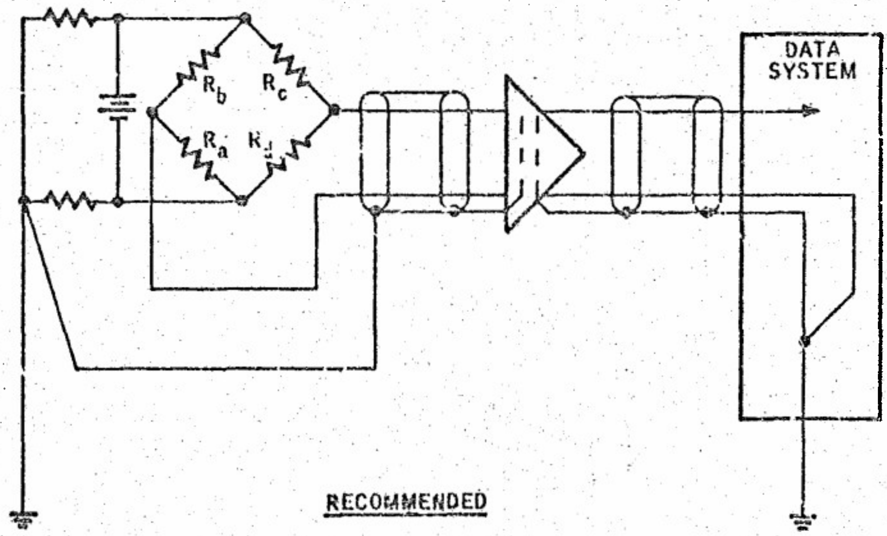


FIGURE 2-27
Bridge Transducer with Isolated Differential Amplifier.

Figure 2-28 illustrates a complete design of a grounded type thermocouple system with all major units in the transmission path from test stand to the recording device.

b. Ungrounded Transducers - Shown in Figure 2-29 are floating transducers which are in common use at many rocket test facilities. These are floating or unbonded thermocouples and wheatstone bridge type transducers. The grounding procedures applied to these transducers will be representative of the requirements of most ungrounded transducers.

In the first two figures, Figure 2-29A and 2-29B, are shown two configurations of floating thermocouple type transducers. Each transducer has a metallic enclosure and the enclosure is connected to the shield. In Figure 2-29A, the enclosure or case is grounded, thus the shield is also grounded. If the load on the signal line is a single-ended amplifier as shown, the shield should not be connected to the amplifier. The shield must be grounded at only one point, preferably at the transducer end, as explained for grounded transducers. However, if the load is an isolated amplifier as in Figure 2-29B, it is not necessary to connect any part of the circuit to earth ground. Certain types of non-isolated differential amplifiers require that a transducer ground path be provided for proper amplifier operation. The amplifier manufacturer should be consulted in this regard.

Figure 2-29C represents a typical ungrounded bridge circuit using an excitation power supply which is balanced to ground. The transducer and power

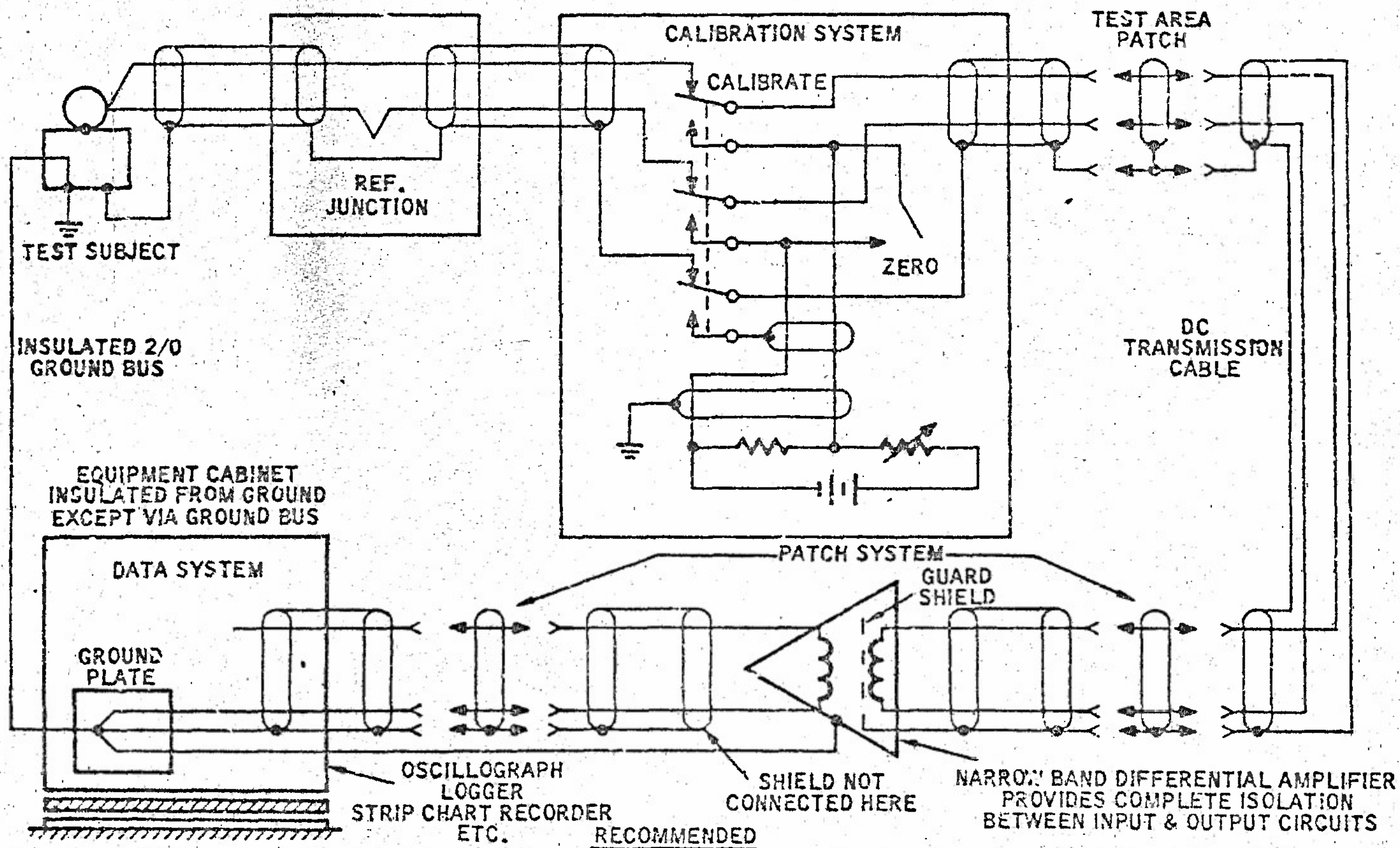
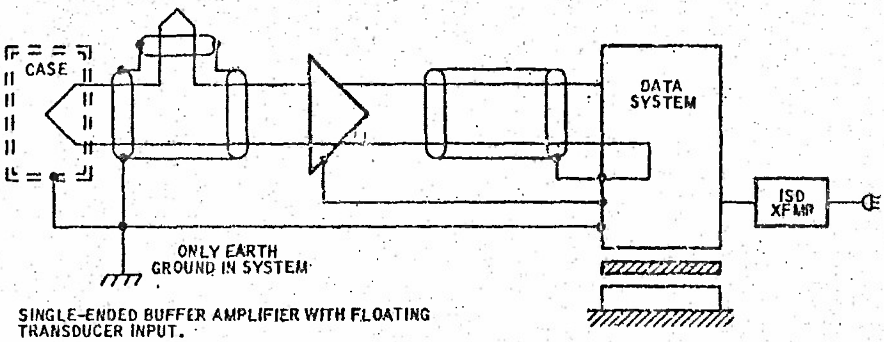
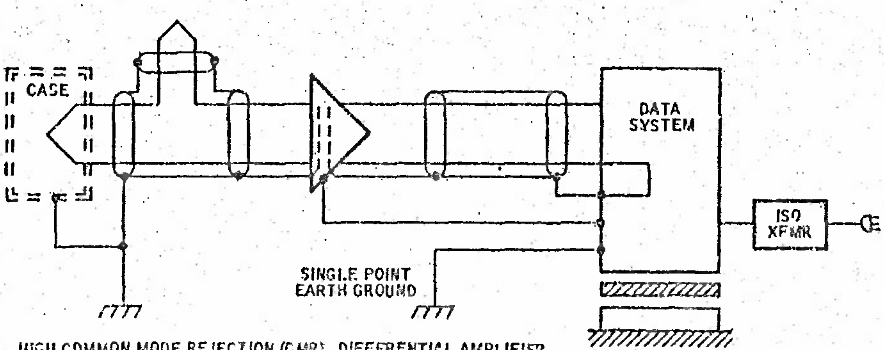


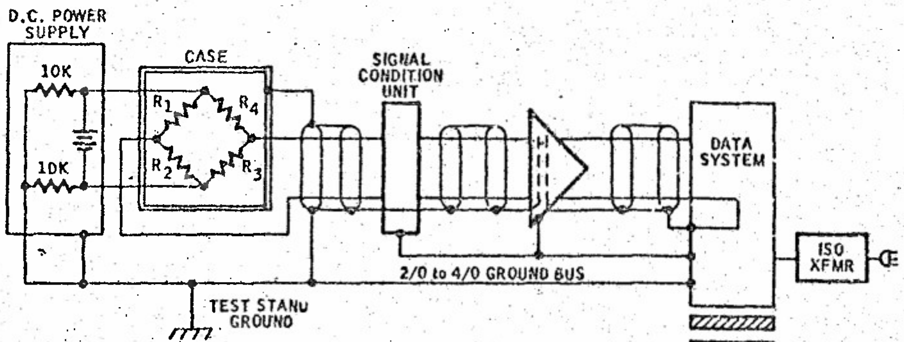
FIGURE 2-28
Grounded Transducer System



SINGLE-ENDED BUFFER AMPLIFIER WITH FLOATING TRANSDUCER INPUT.



HIGH COMMON MODE REJECTION (CMR), DIFFERENTIAL AMPLIFIER WITH TRUELY ISOLATED INPUT AND OUTPUT. TRANSDUCER AND INPUT CABLE SHIELDS FLOATING.



BRIDGE TYPE TRANSDUCER WITH SIGNAL CONDITIONING USING HIGH CMR DIFFERENTIAL AMPLIFIER. ALL PREVIOUS GROUNDING TECHNIQUES USED. BY USING HIGH CMR DIFFERENTIAL AMPLIFIERS, A SINGLE EXCITATION POWER SUPPLY CAN BE USED IN MULTIPLE TRANSDUCER SYSTEMS EXCITATION POWER SUPPLY IS BALANCED TO GROUND TO ELIMINATE POWER SUPPLY COMMON MODE VOLTAGE.

RECOMMENDED

FIGURE 2-29

Floating Transducers

supply are shielded by their cases and grounded at the test stand ground with the system ground bus and cable shields.

Design rules for using ungrounded transducers:

1. Use shielded twisted pair for thermocouple wires wherever possible.
2. Always ground shields of transducer input cables as near transducer as possible and at only one point.
3. Provide a continuous shield "blanket" for all transducers and cabling.
4. When using an isolated amplifier as a load for a floating transducer, connect guard shield to input cable shield.

Figure 2-30 shows an overall bridge circuit instrumentation for a typical application where isolated differential amplifiers are used as well as a common DC excitation power supply for the bridge circuits.

2.2.1.2.2 Multiple Test Stands

So far, only single channels have been considered. This is rarely the case in modern data instrumentation systems. It is more common to use from 10 channels to 200 or more channels per system. In some cases, it is even possible to have two or more test stands with 100 or more channels each which can be routed or patched into the data system either simultaneously or at different times. Normally, only one test area will be used at a time. This is recommended since the separation distance between the two test areas can be several hundred yards. This separation of grounds can develop a considerable common-mode voltage between the two areas and a different common-mode voltage will exist between each test area and instrumentation area.

If two or more test areas are being utilized in one data instrumentation system, different common potentials will be applied to the input of the data instrumentation equipment as it is connected to each test area.

As shown in Figure 2-31, a common-mode potential E_{cm} will cause a current to flow through the low impedance side of the bridge circuit of one channel and back through the low impedance side of the other channel. There are two approaches to this problem: (1) use isolated differential amplifiers in each signal line with high common-mode rejection ratios (one million to one is typical); and (2) use switched ground returns from each test area. In the second method, a single connection is made to the instrumentation equipment ground point from all test areas through a multi-position switch of sufficient size to carry the return current as well as any fault current caused in the AC power circuit.

As shown in Figure 2-32, a ground loop path for common-mode current is broken by the switch, thus breaking the ground loop from one test area to another through the data system and ground bus wire resistance.

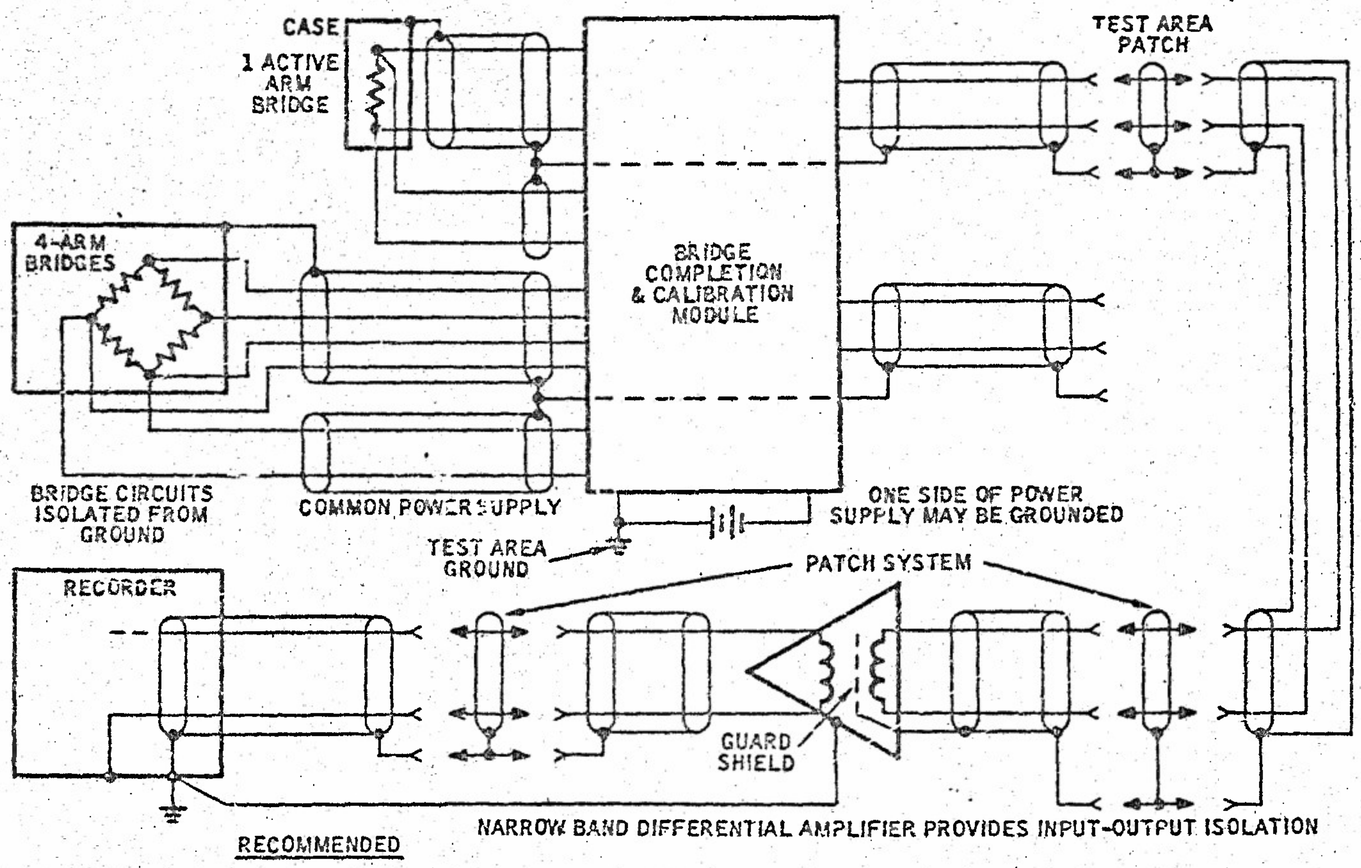


FIGURE 2-30
Bridge System With Common Power Supply

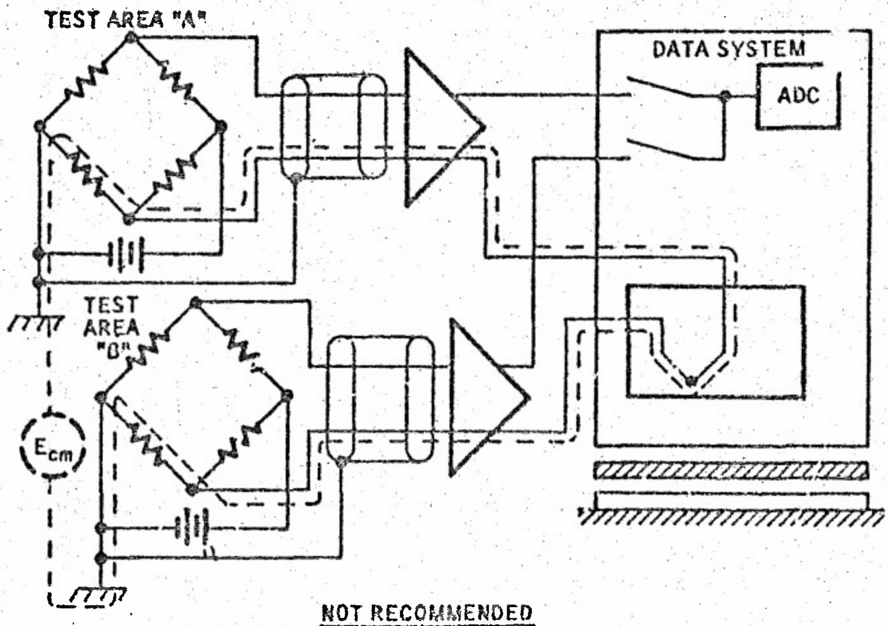


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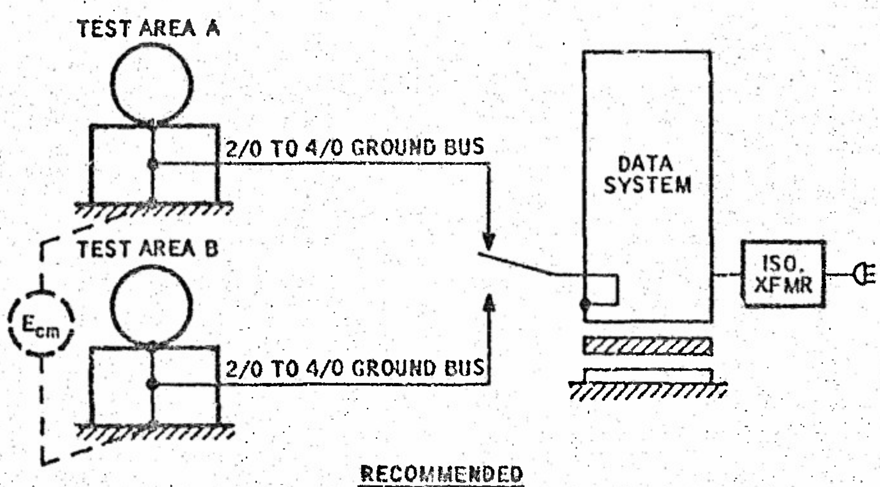
FIGURE 2-31

Earth Potentials Between Two Test Area Grounds Causes Common-mode Potentials in Instrumentation



RECOMMENDED

FIGURE 2-32

Earth Potential Effects Between Test Areas Eliminated by use of Switched Ground Bus Wires

In addition to the ground loops between test areas, it is obvious that ground loops can also occur between channels at the same test area. Precaution must be taken to insure that all shields are isolated from each other, except at the ground point, and that each channel is clear of any unintentional grounds. This is easily verified by lifting all wires from common ground point and taking a continuity check of all lines and shields to ground. Figure 2-33 shows a typical instrumentation system grounding design in which all recommended grounding techniques required to obtain a "minimum-noise" instrumentation system are utilized.

2.2.1.2.3 Digital Signal Grounds

The increasing use of digital processing equipment in data acquisition brings with it many new and interesting problems which are not usually found in an all analog system. Among them is the noise generated by very fast level changes caused by switching circuits within the system. A digital circuit operates by recognizing the state of a two-level voltage or current signal, the speed of the system is therefore limited by the speed at which the levels can be changed. As the speed of the digital systems are increased the noise generated by these very rapid level changes is also increased.

Before an attempt is made to reduce this noise, it is important to know where it comes from and how it is transmitted.

In the wiring of a digital system there exist pulse waveforms which contain high frequency components caused by such things as the system clock and trigger pulses used to change the state (binary 1 or 0) of logic elements. These waveforms are being transmitted between one point and another within the logical building blocks of the system. Typical systems have 6 V transitions from each binary level to the next which can occur in from 0.2 USEC to 10 nanoseconds. At 0.1 USEC, this transient would have a basic frequency component of at least 2.50 MC. The actual pulse rate of the logic-levels may be occuring at a relatively slower rate, 100 KC to 500 KC for example. It is the higher frequency components of the switching transients which are transmitted from wire-to-wire by the coupling capacitance and inductance between them. This type of noise coupling is easily recognized by its differentiated or "spiked" waveform.

If a typical logic waveform is examined, Figure 2-34, a better understanding may be obtained of the high frequency components which are generated.

The transient may be regarded as one-quarter of a sinewave, the duration of which is 0.4 USEC and the frequency of which is 2.5 MC. A typical waveform would be a band of frequencies extending from the first harmonic up to 2.5 MC. Pickup in adjacent wiring is caused if the wiring has a resonant frequency which is within this band of frequencies.

In Figure 2-35A a typical wiring configuration is shown with the wire-to-wire capacitance C_1. In wire (1) is a clock pulse whose waveform is a square wave

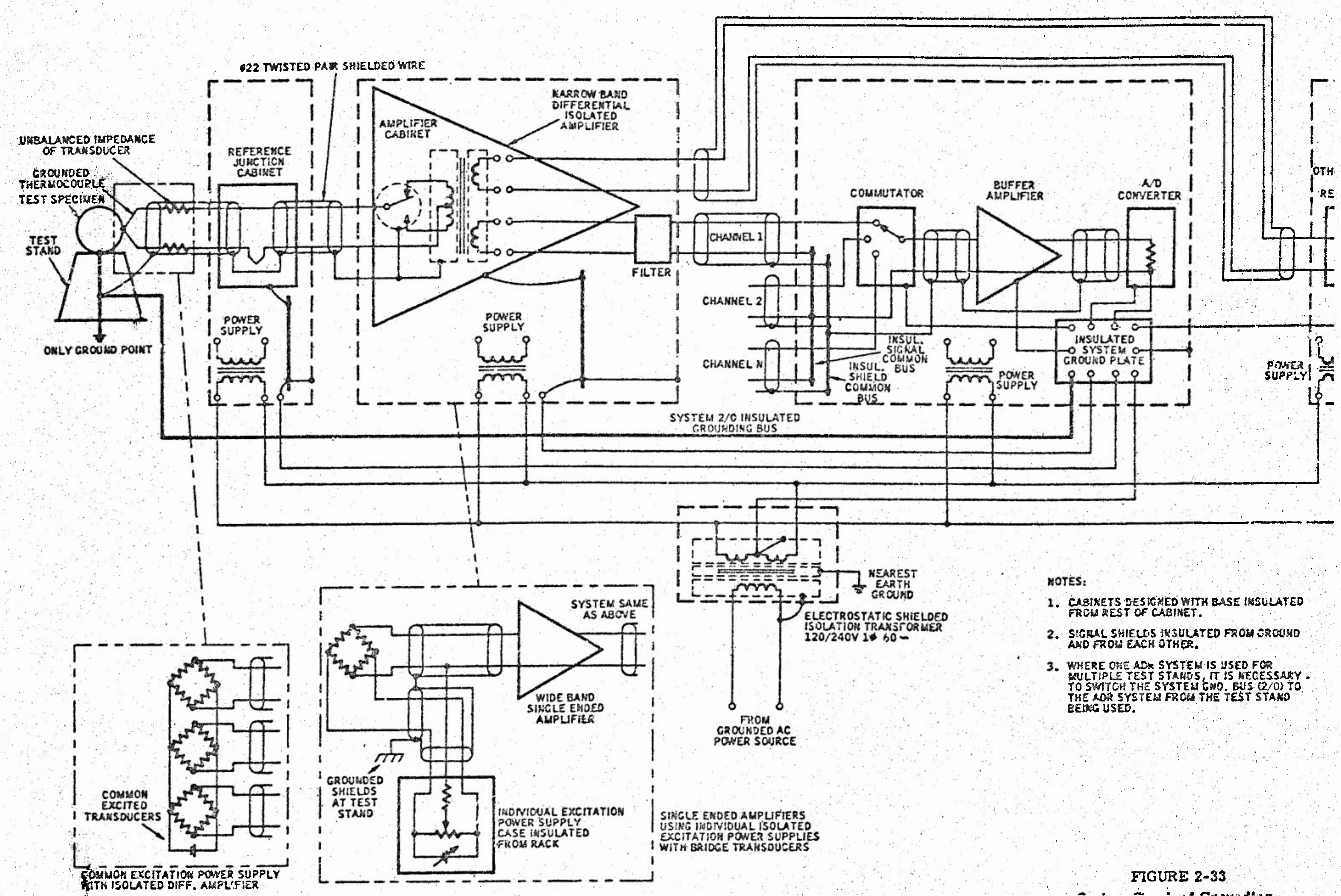

#22 TWISTED PAIR SHIELDED WIRE
UNBALANCED IMPEDANCE OF TRANSDUCER
GROUNDED THERMOCOUPLE
TEST SPECIMEN
TEST STAND
ONLY GROUND POINT
REFERENCE JUNCTION CABINET
POWER SUPPLY
AMPLIFIER CABINET
NARROW BAND DIFFERENTIAL ISOLATED AMPLIFIER
POWER SUPPLY
FILTER
CHANNEL 1
CHANNEL 2
CHANNEL N
COMMUTATOR
BUFFER AMPLIFIER
A/D CONVERTER
INSUL. SIGNAL COMMON BUS
INSUL. SHIELD COMMON BUS
INSULATED SYSTEM GROUND PLATE
POWER SUPPLY
OTH
RE
POWER SUPPLY
SYSTEM 2/0 INSULATED GROUNDING BUS
NEAREST EARTH GROUND
ELECTROSTATIC SHIELDED ISOLATION TRANSFORMER 120/240V 1ϕ 60~
FROM GROUNDED AC POWER SOURCE
SYSTEM SAME AS ABOVE
WIDE BAND SINGLE ENDED AMPLIFIER
GROUNDED SHIELDS AT TEST STAND
INDIVIDUAL EXCITATION POWER SUPPLY CASE INSULATED FROM RACK
SINGLE ENDED AMPLIFIERS USING INDIVIDUAL ISOLATED EXCITATION POWER SUPPLIES WITH BRIDGE TRANSDUCERS
COMMON EXCITED TRANSDUCERS
COMMON EXCITATION POWER SUPPLY WITH ISOLATED DIFF. AMPLIFIER
NOTES:
1. CABINETS DESIGNED WITH BASE INSULATED FROM REST OF CABINET.
2. SIGNAL SHIELDS INSULATED FROM GROUND AND FROM EACH OTHER.
3. WHERE ONE ADs SYSTEM IS USED FOR MULTIPLE TEST STANDS, IT IS NECESSARY TO SWITCH THE SYSTEM GND. BUS (2/0) TO THE ADR SYSTEM FROM THE TEST STAND BEING USED.

FIGURE 2-33

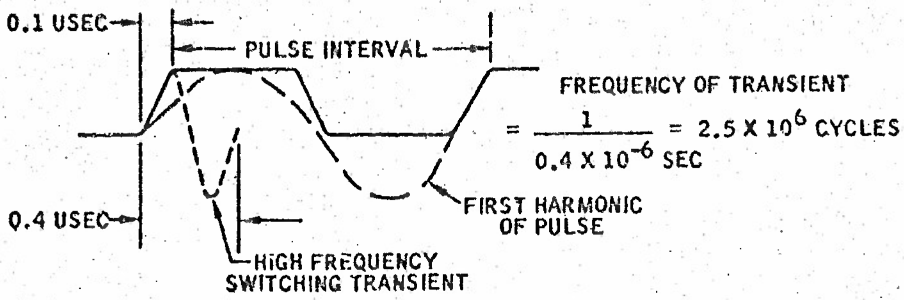


FIGURE 2-34

Typical Logic Waveform

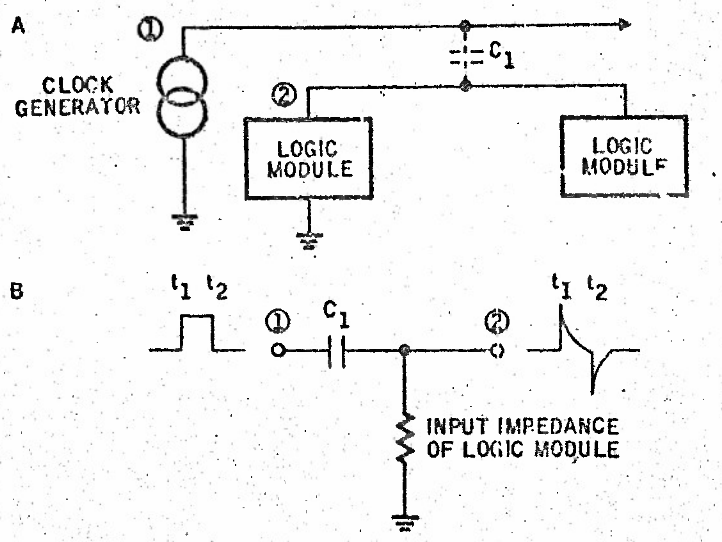


FIGURE 2-35

Typical Wiring Configuration

pulse, wire (2) is located at a distance which determines the value of C_1. The equivalent circuit of the configuration, Figure 2-35B, shows the resultant differentiated pulse in wire (2) as a result of coupling capacity C_1. The capacitance can be minimized by using a high dielectric constant insulation material on the wires and by using the thickest possible insulation material, Teflon is recommended.

Another problem frequently found in digital systems are those which operate using a synchronized pulse train (clock) which controls each sequence of its operation. Because each pulse occurs simultaneously and occurs throughout

the digital wiring the instantaneous current at the rise and fall of each pulse can approach magnitudes in the order of 200 to 300 AMPS. This high current at the rise and fall of the pulse creates a large magnetic field that will radiate throughout the system causing intermittent triggering of circuits which can upset the entire operation. This problem can be minimized if the clock lines are twisted with a grounded wire to reduce the magnetic field and cause a coupling of a certain amount of the magnetic field to ground.

Because of the coupling problem it is recommended that digital systems be wired using a point-to-point method rather than routing signals in a bundle or neat paralleled cables. Figure 2-36 shows a photograph of actual wiring on the rear of a typical logic card rack. The point-to-point wiring used in these card racks is utilized within each individual card rack because all high speed logic, where possible, is confined to within individual card racks. This minimizes the use of long wires going from one rack to another carrying very fast rise time pulses. Where interconnections are necessary between card racks, they should be as short as possible and should always be made as a fan out from one point if the signal is to be distributed to several points. Since all points are effectively in parallel with the fan out distribution point, each line will be short as compared to the length of a line which connects all the points as a series string. Since the inductance of a wire is directly related to its length, the overshoot and ringing (caused by inductance) can be reduced up to 75% by the fan out wiring method.

Because of the capacitive coupling and magnetic fields resulting from the very fast rise and fall times of digital pulses every precaution should be taken to minimize the effects by twisting clock lines with ground wires and by point-to-point wiring to reduce capacitive coupling. The ground wires in a digital system are important and should receive careful consideration because they will also be carrying the pulses. The ground wires cannot be considered at zero reference potential until they reach the common ground point. Since the ground wire will have an inductance and resistance, the current from the digital pulses distributed into the ground wires will create potentials along the ground wire inductance and resistance. All circuits sharing the ground wire can be effected by these ground potentials (e.g., sensitive trigger circuits). When many parallel paths in the ground wiring are provided, the ground current will be distributed and divided into smaller amounts in each wire thus reducing the potentials along the wire. Therefore, a general rule to follow in the grounding of digital circuits is to wire each ground circuit so that it will have individual convergence to the ground point. Also the grounding should follow a treeing effect so that all branch wiring will run to the main ground point without forming closed paths.

Illustrated in Figure 2-37 is a wiring method that provides multiple paths to ground by running a minimum of four vertical ground buses between logic card racks. Nearby ground circuits are then wired to the ground buses forming a

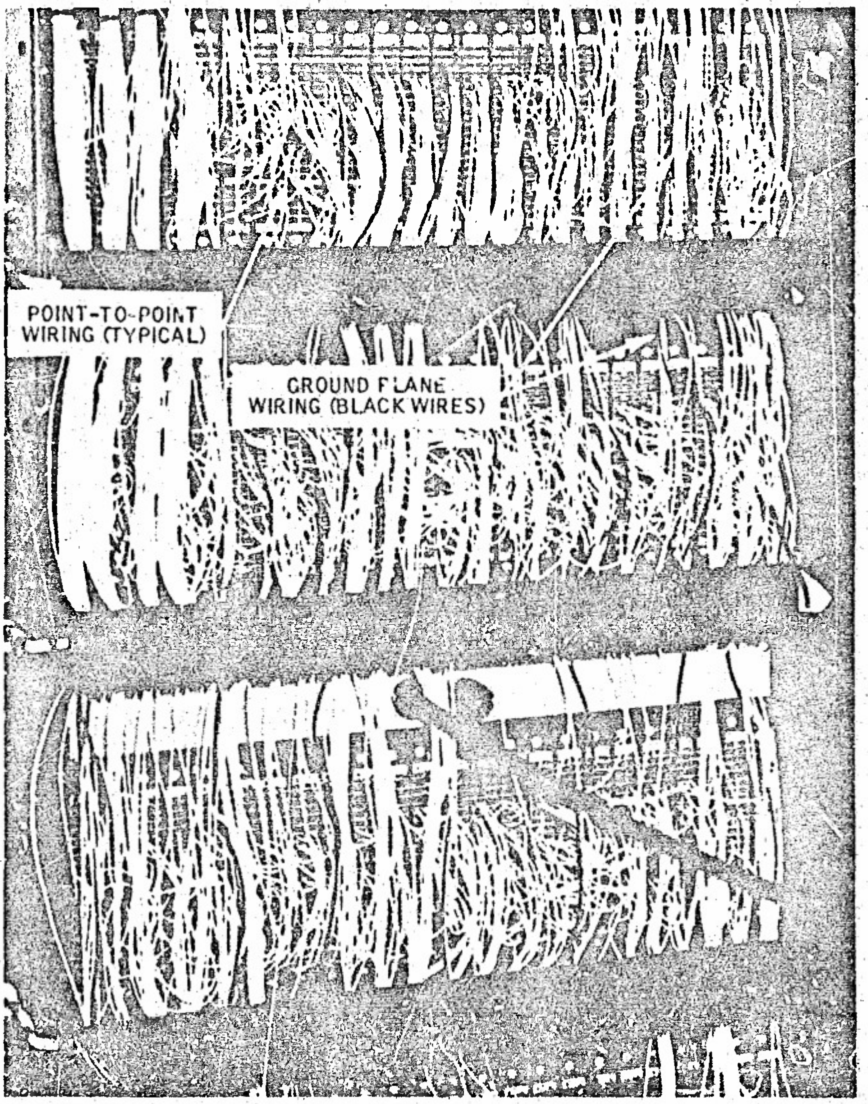
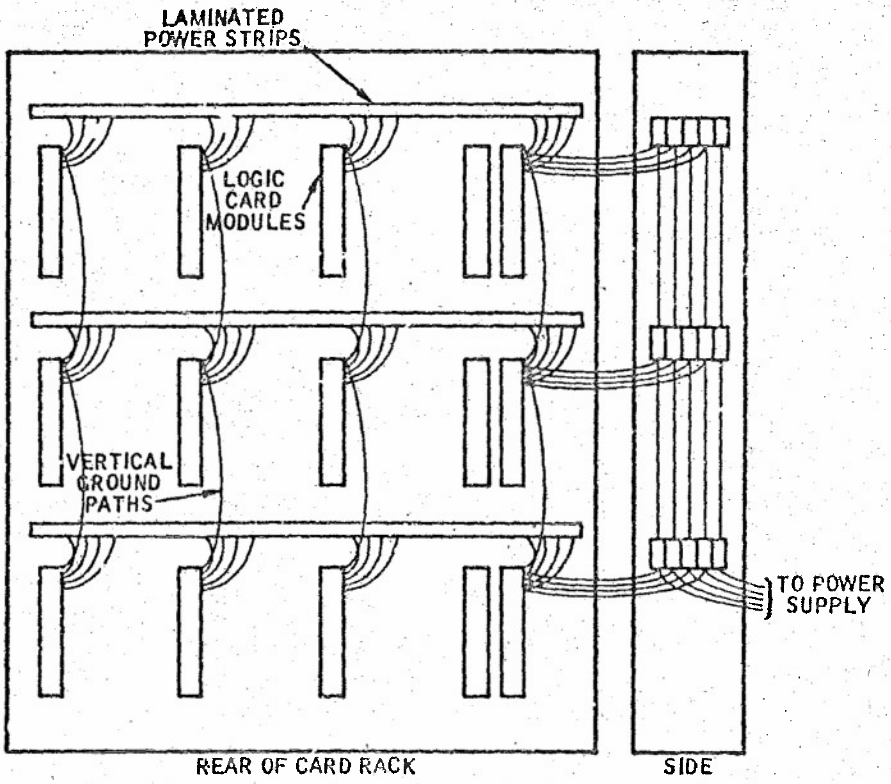


FIGURE 2-36
Rear View of Logic Card Rack Wiring



RECOMMENDED

FIGURE 2-37

Ground and Voltage Routing in Logic Card Racks

treeing effect of ground wires. Power to the card racks is distributed between card racks using a horizontal laminated low inductance DC power buses.

In an overall system where both analog and digital circuits must be housed in the same equipment cabinet, it is important to keep as much physical separation between them as possible, e.g., at opposite ends of the cabinet. The common ground plate in the system can be located in the center of the cabinet or two ground plates can be utilized, one for analog ground and one for digital ground. These two ground plates must then be tied together with low inductance connections and then tied to the system ground bus line described earlier. A typical ground plate installation in a small digital system is shown in Figure 2-38.

Each card rack uses a horizontal, laminated low inductance power strip. Power is distributed between card racks with a vertical power strip on barriers. To effectively reduce overall inductance of the ground further, at least four wires are used between each card rack ground.

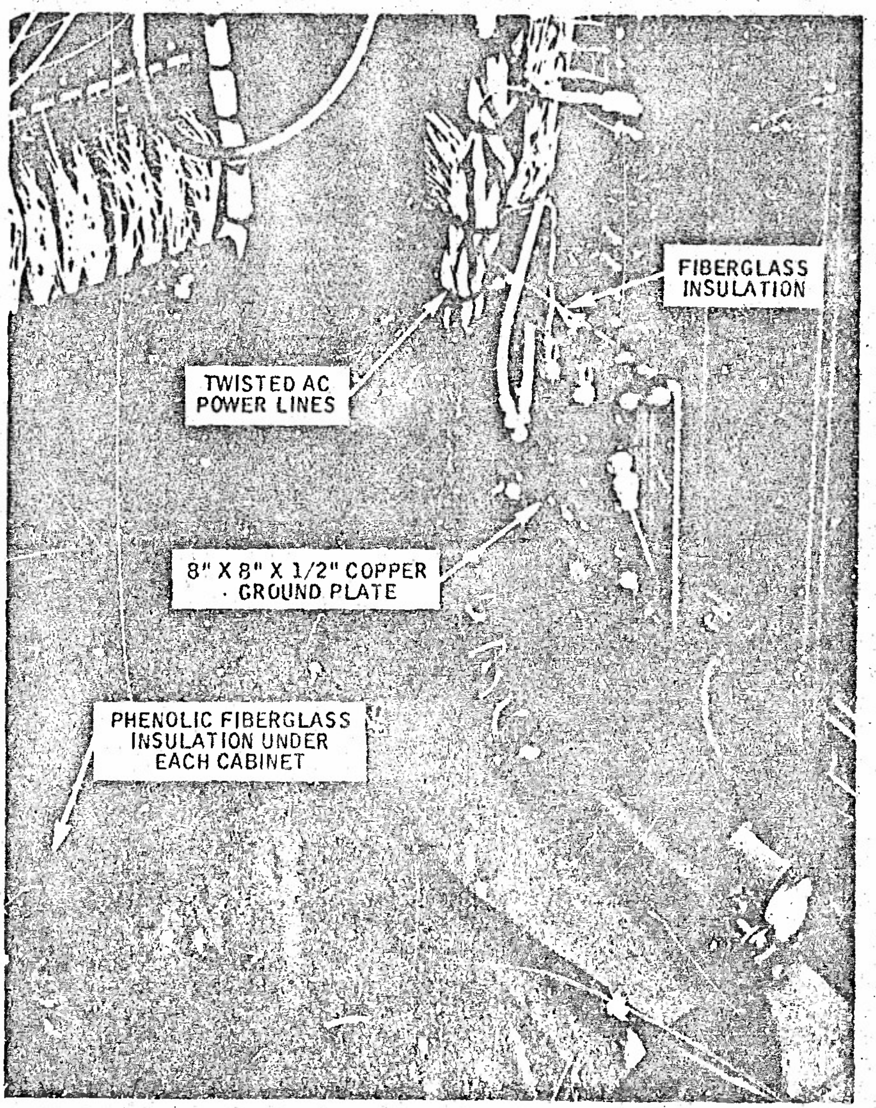


FIGURE 2-38
System Ground Plate Installation

2.2.2 SHIELDING

Shielding may be necessary to either keep various signals or noise confined within certain limits or it may be necessary to keep various signals or noise out of a certain area, such as low-level instrumentation cables. In order that effective shielding be provided, the type of the signal or noise which is being shielding must be known, e.g., electrostatic fields, or electromagnetic fields. Each of these have been discussed earlier and more data may be obtained by referring to references listed in the Bibliography.

Electrostatic fields have a characteristic which make them rather simple to shield against. Electrostatically induced current in a shield must flow through the surface resistance of the shield and will not penetrate the shield if it is a fairly good conductor. Thus, in instrumentation cables it is common to find copper braid or copper stranded wrap as an electrostatic shield. There are several good forms of electrostatic shields available for cable manufacturers, among them are stranded copper braid, stranded copper wrap, and double braided shields.

Electrostatic fields predominate over magnetic fields in most instrumentation areas and the use of a copper braided mesh shield is fairly effective. However, if there are magnetic fields present such as those generated by high current transformers, and high current AC power circuits the copper braid provides little shielding effect. To be effective against magnetic fields a conducting shield should have a thickness that is several times the skin depth δ:

Where $\delta = 5033 \sqrt{\rho/\mu f}$

δ = skin depth

ρ = resistivity of conductor, ohms per centimeter cube

f = frequency, cycles per second

μ = magnetic permeability of shield material (permeability of air equals one), for low flux densities μ is the initial permeability.

For copper at 20° the skin depth is

$$\delta\,(\text{cm}) = \frac{6.62}{\sqrt{f}}$$

The attenuation of a magnetic field whose flux is normal to the conductor (shield) is

$$\text{Shield attenuation} = 8.69\,\frac{a}{\delta}\ \text{db}$$

a = shield thickness, cm

δ = skin depth

Magnetic flux which attempts to pass through a low resistivity shield, such as copper or aluminum, induces voltages which cause eddy currents in the shield. These eddy currents appose the direction of and tend to prevent the penetration of magnetic fields through the shield. The eddy currents are a desired effect in any low resistivity magnetic shield. If a joint, break, or hole exists in the shield, its effectiveness is reduced.

A high permeability ferrous material such as iron is the best magnetic shield because magnetic flux will actually be absorbed by the ferrous material. The iron or iron alloy will have a lower reluctance (resistance to magnetic flux) than air causing a magnetic field to be attracted to it. The higher the permeability of a material the better magnetic shield material it is, nickel-iron alloys have permeabilities in the range of 10,000 to [illegible],000. The permeability of a magnetic material is a ratio of the flux density to the magnetizing force, B/H.

Shielding of power conductors is a method which may be used to attenuate both electrostatic and electromagnetic coupling between power conductors and susceptible data acquisition system conductors.

Of the various wiring methods available to the facilities design engineer, many surround the insulated power conductors with a grounded metallic enclosure for the physical protection of the wire or cable. The shielding effect of this enclosure can be put to good use in the design of a test facility. The metallic enclosures used to protect power conductors may be cylindrical or rectangular, smooth or corrugated and may be part of a complete power cable assembly or may be a separate conduit or duct into which the conductors are pulled. The enclosure may vary in thickness from a 0.005 inch thick spirally wrapped metal tape to a conduit wall 1/8 inch thick. The materials in common use today are steel, aluminum, and copper.

The electrostatic coupling between power conductors and other physically paralleled conductors will be eliminated by any grounded, conducting surface completely surrounding the power conductors. The containment of the electrostatic field is not dependent upon either the thickness or material of the conducting surface so long as the surface presents a low impedance to ground at all points and completely surrounds the power conductors.

The electromagnetic field at power frequencies is only partially attenuated by a metallic enclosure and the degree of attenuation depends upon the material and its thickness. The shielding effect is proportional to the permeability of the material and varied directly, though not linearly, with the thickness. (As the total thickness increases, a unit incremental increase in thickness results in a diminishing increase in attenuation.) It follows that a ferromagnetic enclosure is a far more effective electromagnetic shield than a non-ferromagnetic and that thickness is a desirable characteristic.

Of all of the conductor enclosures available to the test facility design engineer, rigid steel conduit most closely approaches the ideal shield. In order to determine the effectiveness of rigid steel conduit as an electromagnetic shield at power frequencies, tests were conducted which compared the magnetic field strength near unshielded conductors carrying a constant 60 cycle current against the same conductors installed in steel electrical metallic tubing (thin-wall) and rigid steel conduit. It was found that the electrical metallic tubing attenuated the field approximately -7 to -8 db while the rigid steel conduit provided -16 to -18 db attenuation.

2.2.3 PAIR TWISTING

As described in Section 2 under Electromagnetic Radiation, magnetic fields can penetrate the area between two conductors and induce a potential in an instrumentation line. If the area between the two conductors could be reduced to zero, the induced voltage would also be reduced to zero. However, the insulation around the wires prevent a zero area between the conductors. Coaxial cable accomplishes an effective zero area by surrounding one conductor with another conductor. The other conductor is the shield and is grounded to bleed off stray currents. If the shield in a coax line is one side of signal, stray currents will cause noise errors in the measurement.

If a two wire transmission line is twisted, the voltages induced in the line will be proportional to the area between the conductors. Figure 2-39 illustrates that twisting will reduce the area between the wires. Shown is a twisted pair of wires terminated in a resistive load R_L and connected to a source with an internal impedance of R_1. A uniform magnetic field is imposed upon the wires.

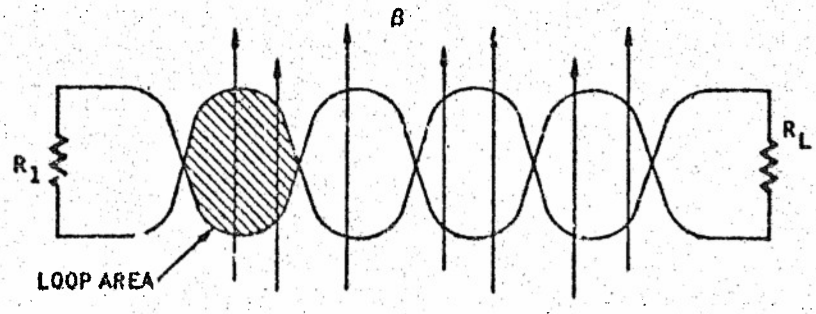


FIGURE 2-39
Area Between Conductors Reduced by Twisting

A current will be induced in the circuit proportional to the circuit loop area and the rate of change of the magnetic field. It can be seen that each loop or section will have a finite area which is susceptible to induced voltages caused by the impinging magnetic field. As the wires are brought closer together by twisting, the loop area is reduced and the induced voltage will also be reduced.

When a magnetic field is created around the wires due to a current flowing in the wires, then each loop will have a magnetic field equal in magnitude but opposite in direction. Thus, as the wires are brought closer together the fields will tend to cancel one another because the fields produced by each wire are in opposition and the opposing force will effectively cancel the field.

It is a common practice to twist all instrumentation wire in order that a certain amount of magnetic field rejection can be achieved. Likewise, it is highly recommended that all power circuits which distribute 60 cycle AC power to the instrumentation equipment be twisted with as many twists per foot as possible. The more twists in the wires the less will be the effective area between the conductors. The area between the wires is limited by the insulation thickness around each wire.

Actual tests disclose that twisting of transmission line pairs can reduce noise due to 60 cycle pick-up by significant orders of magnitude.

A type of wire is available which offers a marked improvement over the usual twisted pair of wires (see Figure 2-40). This wire is actually weaved not twisted, and consists of four wires. The weave is arranged so that two interlocking loops are produced. To form a two conductor cable a pair of wires are connected together at both ends of the cable, thus forming one conductor. The other pair of wires are connected in the same way forming the other conductor. This means a smaller wire size can be used in each conductor with a greater degree of flexibility in the overall cable. The electrical advantage is that much tighter loops are formed between each conductor, and the weaving process aids in the cancelling effect of equal and opposite magnetic fields.

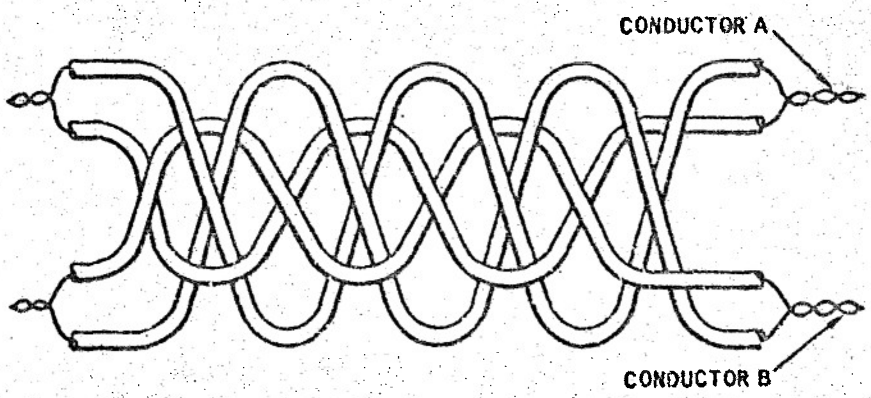


FIGURE 2-40
Weaved Cable

Not much information is available on this wire. However, certain tests show it to be several orders of magnitude better than the twisted pair configuration in rejecting magnetic fields. One manufacturer of this cable is Magnetic Shield Division of Perfection Mica Company, Chicago, Illinois. The cost of this wire is relatively high and its use will be determined by the magnitude of the magnetic fields.

2.2.4 ISOLATION

Isolation is a means of preventing ground loops which may carry noise producing currents. The underlying philosophy of isolation is to electrically isolate the instrumentation system (AC and DC) from earth. The system itself may be regarded then as "floating". Once isolation of the system is achieved then the system is connected to earth through a single ground wire. All other external connections to the system (power, control, data) should be made through an appropriate isolating device. The basic methods of isolation are described below.

2.2.4.1 Isolation Transformers

The transformer is a simple means to provide system isolation because it does not readily couple energy electrostatically from primary input to secondary output. This transformer characteristic is illustrated in Figure 2-41.

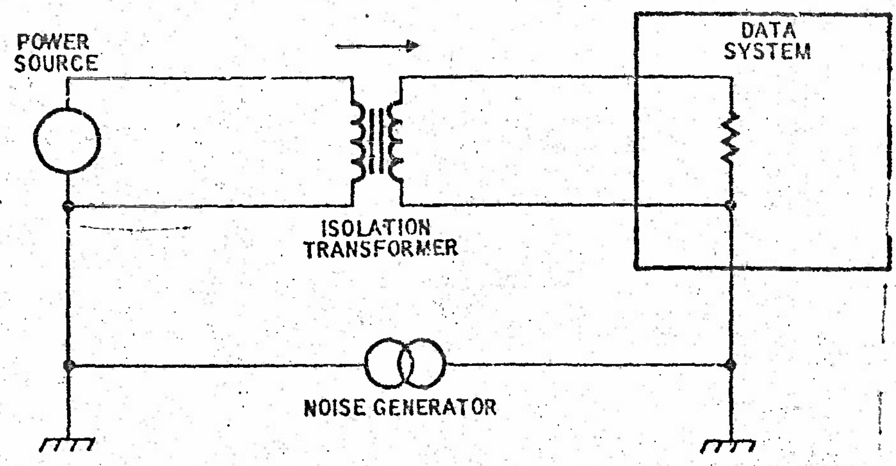


FIGURE 2-41
Isolation by Transformer

Note that currents resulting from noise voltage would be significantly greater were the isolation transformer not present in the power input circuit. Although a simple transformer does provide isolation, it can be significantly improved by the use of primary and secondary shielding.

Figure 2-42 shows how noise can be transferred from primary to secondary. The primary noise is represented by a noise generator between a long line such as a power transmission line and ground. Because a power line can come from great distances it can bring with it a variety of noise such as radio and television signals, ignition static from automobiles, switching arc noises, and lighting. To keep this noise from reaching the secondary a conducting foil shield is placed between the primary winding and the secondary winding and grounded. This type of shield is electrostatic and is called a Faraday shield. The shield does not significantly affect the magnetic coupling of the transformer. The purpose of the shield is to offer a lower impedance path from the primary to ground than from the primary to the secondary winding. Electrostatically induced currents are therefore carried to ground rather than through secondary circuitry.

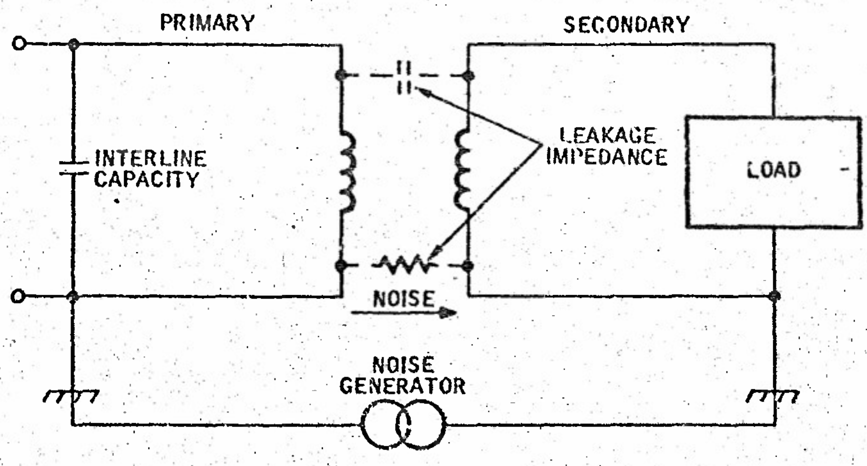


FIGURE 2-42
Transfer of Noise Through Transformer Windings

Since the shield may not cover the entire primary or secondary windings, there is a fringing of electrostatic fields around the shield. Because of this fringing effect, noise can still be coupled across the windings. By enclosing the primary winding completely in a shield, as illustrated in Figure 2-43, the fringing can be reduced. This type of shield is called a box shield.

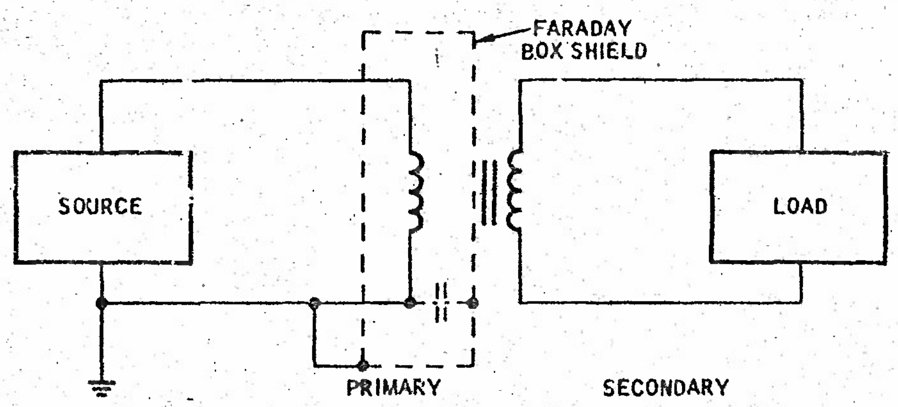


FIGURE 2-43
Faraday Box Shielded Transformer

This type of Faraday shield reduces to an absolute minimum the interwinding capacitance from primary to secondary. Production transformers are available which have interwinding capacitance less than 0.005 pf and with leakage resistance in excess of 10,000 megohms.[16]

A double shield around the transformer windings effectively increases the winding impedance to ground or nearby shields thereby increasing the noise rejection capabilities of the transformer. The second box shield, shown in Figure 2-44, is called a guard shield. The guard shield can be used on the primary or secondary winding or both depending upon the circuit requirements. The usefulness of a guard shield is shown in Figures 2-45 and 2-46. A Faraday box shielded transformer, shown in Figure 2-45, uses a floating rectifier bridge network. The bridge has a high leakage (isolation) impedance (R) to ground. The secondary box shield is connected to earth and the effect of the winding to shield capacitance C_1, C_2 will be to shunt the high leakage impedance of the bridge. The power supply will then become more susceptable to noise pick-up through this lower impedance. By placing a second box shield, the guard shield, inside the first shield (see Figure 2-46) and terminating it to one conductor of the winding, usually the center tap, the guard shield will then take on the potential of the winding thereby returning the winding-to-shield capacitance back to the winding and greatly increasing the impedance between shields. Thus, the winding-to-earth ground impedance approaches that of the leakage impedance of the bridge network.

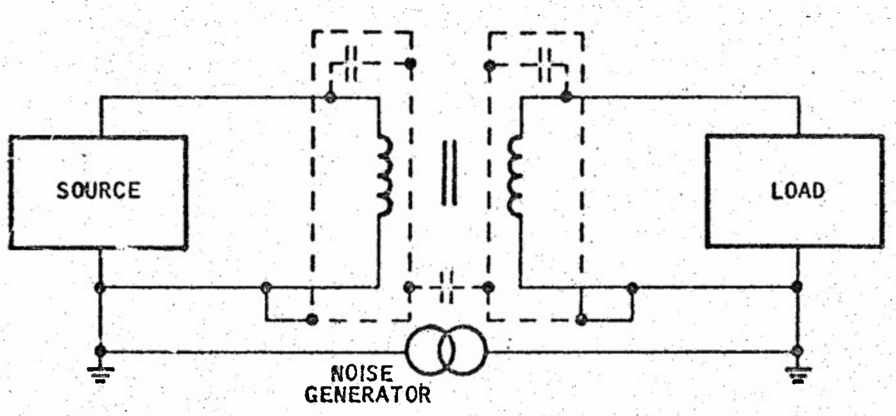


FIGURE 2-44
Box Shielding on Primary and Secondary Windings

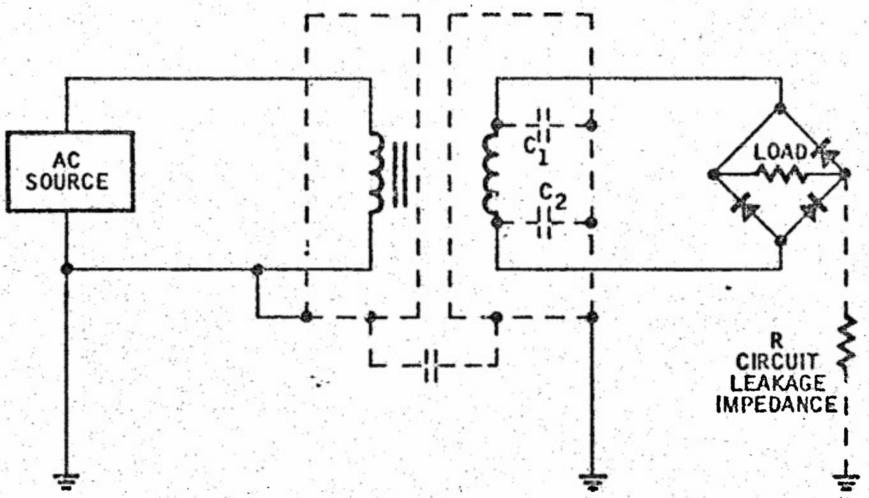


FIGURE 2-45
C_1 and C_2 = Winding to Shield Capacitance

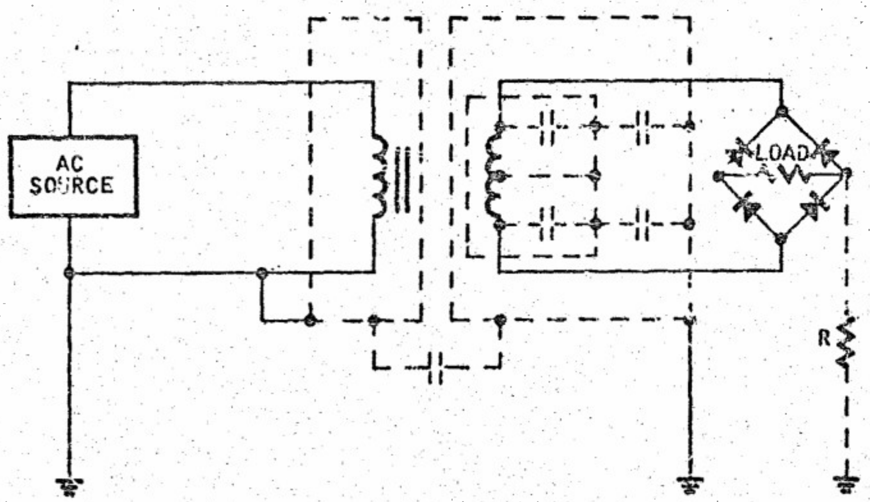


FIGURE 2-46
Guard Shield Used in Secondary to Increase Isolation Impedance to Ground in Secondary Circuitry

Advantages of using box shielding over the primary and secondary include, prevention of noise from going in either direction (from primary to secondary and vise versa), and increased capacitance between shields provides a lower impedance path to ground for noise, and the guard shield greatly increases the isolation impedance of the windings to ground as well as across the windings.

It is recommended that Faraday box shielded transformers be utilized in the following instrumentation applications:

1. Instrumentation DC power supplies
2. Signal and chopper input transformers in DC low level data amplifiers
3. Primary AC power for an instrumentation on system to block power line noises caused by motors, relays and other sources as mentioned earlier

It may be adviseable in cases of extreme noise environments to shield the main facility electrical service transformer(s). Large transformers can be designed and manufactured with electrostatic shielding between windings at an increase in cost of approximately 25 percent.

Table 2-2 specifies the types of isolation transformers which are in common use. For more specific information concerning the specifications and testing of transformers refer to the article given in the Bibliography titled, "Specification and Testing of Shielded Transformers" by Bernard I. Sommer and Gerald W. Plice.

Transformer Type	Parameter	Typical Value	Remarks
1. DC Power Supply	Voltage	Primary = 113V Secondary = 50 to 115V	
	Frequency	60 or 400 CPS	
	DC Current	100 to 450 MA	
	Rectifier and Filtertype	Full wave	
	Guard Shield?		Recommended for Floating Power Supplies
2. Input and Signal Line	Sources & Load Impedance	Source = 1K Load = 1 MEG	
	Frequency Response	1 KC to 20 KC	
	Power Level	10 to 100 MV	
	Maximum Capacitance between Windings	0.03 pf	
	Common-Mode Rejection	130 db	
	Magnetic Shielding required?		Usually recommended for low level signals.
3. Isolation, Power	Voltage	115V	
	Frequency	60 cycle	
	Volt - Amperes	50 to 2500	
	Working Voltage	115V	
	Maximum Capacitance Between Windings	0.1 pf	
	Common-Mode Rejection	130 db	

The following items should also be considered in specifying transformers:

Maximum case dimensions
Mounting requirements
Environmental Operating condition

TABLE 2-2

Types of Isolation Transformers

2.2.4.2 Spatial Isolation

Spatial isolation is defined as physical separation of power equipment (and other noise sources) from the instrumentation system. It is, in most instances, one of the simplest and least costly means of decreasing coupling between the power system and the instrumentation system. Electromagnetic and electrostatic coupling (e.g., energy radiated from arcs and corona) decrease rapidly with increases in physical separation between source and susceptable circuit. Most planned test facilities have adequate space available to permit considerable separation between power conductors and data transmission conductors, as well as between electrical power equipment and data acquisition system equipment. However, spatial isolation is sometimes limited by the physical dimensions of the facility where power and instrumentation systems must be installed together aboard an aircraft or in confined quarters. In each case, if the design agency is aware of spatial isolation throughout the early phases of planning and design, maximum separation of the electrical power system and the data acquisition system equipment and conductors can be achieved with little increase in cost.

Providing separate and independent electrical services from the utility power substation for the power system and data acquisition system in a rocket test facility should be considered where severe transients and disturbances are anticipated on the facility power system. For example, starting a large motor on the facility power system will cause a sudden momentary drop in voltage. A drop as large as 15% can be tolerated in power system design practice but may cause drift in electronic equipment. The voltage drop caused by the starting of a large motor can be decreased but not eliminated through the use of reduced-voltage starting techniques. Application of fast response voltage regulators in the electrical supply to the data acquisition system equipment will afford a faster recovery to normal voltage but will do little to lessen the initial and transient drops. Transients can be greatly reduced by using line filters with low pass characteristics.

The sudden drop in voltage is caused by the large surge of current (required by a motor at start) being drawn through the impedance of the utility system, such as the main transformer and bus, circuit breakers, cables, and other items which make up the facility power distribution system. Of these items, the main transformer usually constitutes the largest single impedance in series with the motor and, therefore, causes the largest portion of the voltage drop. (An exception might occur if the utility system were small or where the test facility is served at the end of a long line.) If the data acquisition system were fed directly from the utility system through a separate transformer, the data acquisition system would not be subject to that portion of the voltage drop caused by the main transformer and the facility power distribution system. The separate service would not, of course, eliminate that part of the drop caused by the effective utility system impedance.

A secondary advantage provided by a separate service transformer would be the attenuation of conducted radio frequency noise originating in the facility power system.

Points which must be considered in investigating the desirability of a separate service are the extra cost of installation, the higher cost of electrical power if the second service is received directly from a commercial utility, the expected frequency and severity of transients and disturbances generated within the facility, and the degree of isolation from voltage drop that can be achieved, taking into account the relative impedances of the utility power system and facility main transformer. Note also that, while a measure of isolation is provided from conducted radio frequency noise originating within the test facility power system, no attenuation of conducted noise originating on the primary utility system will be provided by installing a separate service. However, high frequency noise originating on the primary utility can be reduced by the use of low pass line filtering in the instrumentation service lines.

A second means which can be employed to provide isolation of the data acquisition system electrical supply from the facility power system is the use of a motor-generator set to supply the data acquisition system. Use of a motor-generator set will completely isolate the data acquisition from conducted radio frequency noise originating in the facility and utility power systems and will almost eliminate voltage drops and disturbances. The major drawback to this solution is the high first cost and the increased maintenance required by the rotating equipment.

2.2.4.3 Equipment Isolation

All the proper grounding procedures as discussed earlier is of little value if the measurement system or test equipment is allowed to introduce ground loops and extraneous noise into the measurement. It is not uncommon to see a failure in an elaborate test set-up because the noise level is greater than the desired signal level. Often it is found, after through trouble shooting, that too many grounds were placed in the measurement circuit and ground loops were formed between test instrument, measurement circuit, and earth ground.

Isolation of certain parts of an instrumentation circuit are mandatory to prevent ground loops and interaction with other circuits. Equipment isolation can accomplish a part of this requirement by establishing a single point at which all equipment cabinets are to be grounded and "floating" all equipment except at the common point. It is necessary that all ground wires connected to the common ground point do not connect with other similar ground wires at other points. The ground wires will form a type of tree with all branches steming from the trunk outward with no connection made at the other end. The common ground point can be placed in one cabinet or bay from which all other cabinets or bays are connected. The ground

point should be sufficiently large to allow many wire connections and of very high conductivity so that a uniform potential may be maintained therein. A rectangular copper plate of approximately 6 inches x 6 inches x 1/2 inch is usually sufficient for this purpose. Wires can be fastened to the plate by drilling and tapping holes to allow bolting of wire terminals. In Figure 2-38 a typical ground plate is shown installed in a small digital data acquisition system. In order that the ground plate be isolated from ground it is mounted on fiberglass insulators.

The equipment cabinets may still be in contact with the ground. However, this can be a serious limitation to the grounding system design.

Figure 2-47 shows a typical test configuration without cabinet-to-ground isolation. The common-mode voltage (noise generators) present in the earth will cause undesired ground loop currents in the instrumentation lines because of the potential differences at the two ground points. This common-mode voltage can be eliminated by isolation of the equipment cabinets from ground. Isolation can be accomplished by non-conductive strips or sheets of plastic such as fiberglass impregnated with epoxy or similar material.

Figure 2-48 shows an actual installation of an equipment cabinet which has been bolted to a metal base using nylon bolts with sheets of fiberglass insulation between the cabinets and metal base. In this way, all the equipment is floating except for one intentional earth ground connection using low resistance 2/0 or 4/0 insulated copper bus wire from the cabinet ground plate to test area ground point as shown in the Figure 2-49.

This provides only one point where the entire instrumentation system is grounded, thus eliminating each common-mode voltage within the system.

The isolation of equipment cabinets during system design and manufacturing is relatively simple compared to the isolation of equipment cabinets in an existing facility. Isolation of existing equipment usually means an extensive overhaul of equipment and an exhaustive check that unwanted ground connections are eliminated and correct ground plate connections are installed.

Metal conduit must also be given consideration in properly isolating a system. If instrumentation cables and/or power cables are connected into the system through metal conduit, precaution must be taken to insure that no electrical contact is made between the conduit and the equipment cabinets. If a distribution panel is provided for power switching to the cabinets, a PVC type conduit may be used between the panel and instrumentation equipment. Conduit used for instrumentation cabling can be fastened to a bulkhead or support member of the building to avoid cabinet-to-conduit contact.

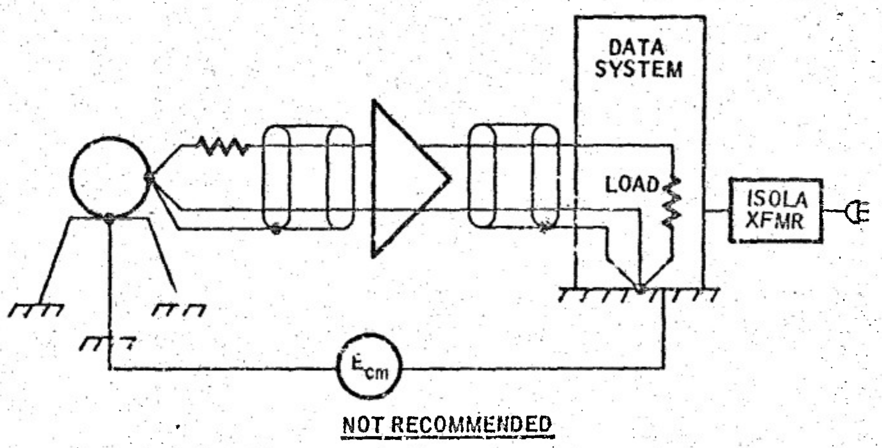


FIGURE 2-47
System Without Cabinet Isolation

Cable trays are used in many test facilities to support instrumentation wiring running from test area to instrumentation area. Like conduit, cable trays should never be electrically connected to the instrumentation equipment. Cable trays and conduit present a problem to low-level instrumentation because each one is usually well grounded to earth. Because the instrumentation cables have a finite amount of leakage impedance through the shields, the closeness of the cables to the conduit and cable trays then provide a possible source of common-mode voltage being coupled into the instrumentation. It is therefore recommended that grounding of the cable trays and conduit follow the same philosophy as grounding of cable shields. That is, earth ground the cable tray and conduit (if possible) at only one point so that the coupling impedance to the common-mode voltage will be as large as possible.

The conduit and cable trays may be isolated from ground by a vinyl covering over the conduit and by using non-conductive mountings on the cable trays. The ground point to earth should be as near the test area (transducer) ground as possible.

2.2.5 BONDING

Electrically mating (bonding) of metallic surfaces to insure electrical continuity to ground of the non-current-carrying portions of electrical equipment and conductor enclosures is one of the most important ingredients of a good grounding system design. Bonding is also the most often abused of the grounding requirements. An improper bonding of equipment will be subject to corrosion, and mechanical stress.

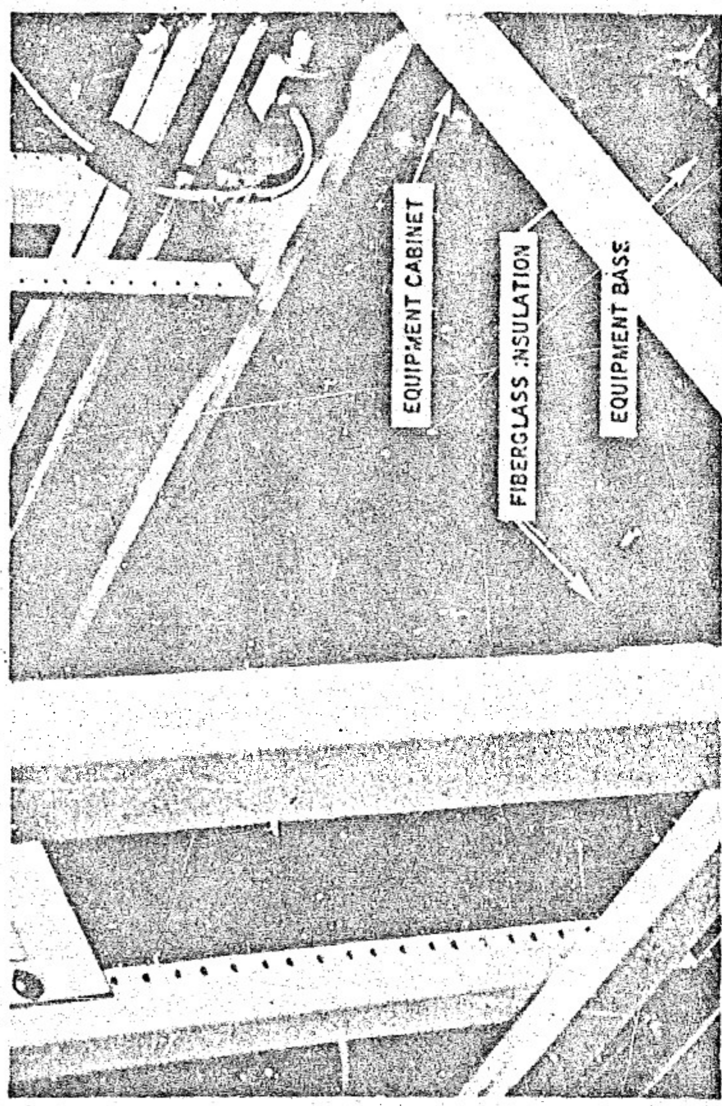


FIGURE 2-48
Equipment Cabinet with Fiberglass Insulation Between Cabinet and Base

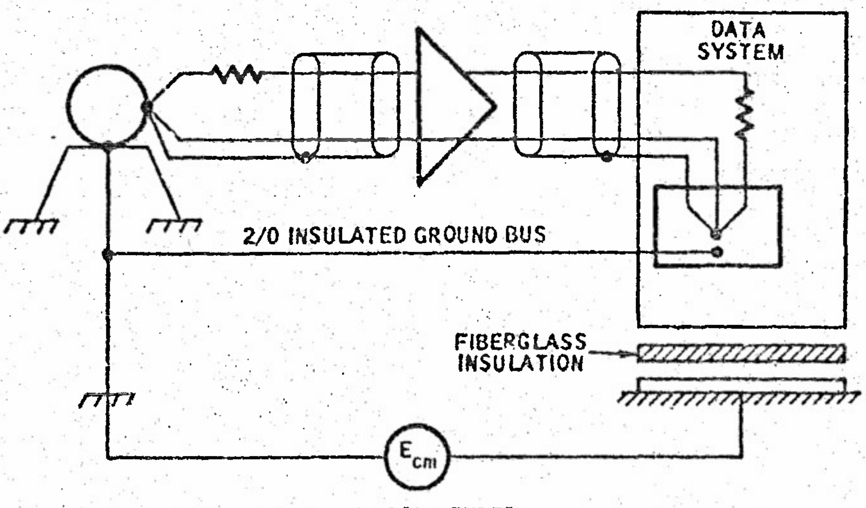


FIGURE 2-49
Isolation Data Systems With Ground Wire to Test Area Ground

The purpose of bonding is primarily one of safety to personnel. If all metallic enclosures of conductors and equipment are provided with a low impedance path to ground, a difference of potential between the enclosures and ground cannot be developed due to an insulation failure within the enclosure. Conversely, if the impedance of the enclosure to ground is high, a person contacting the enclosure and ground, following an insulation failure, could receive a lethal shock.

A bond may consist of the metal-to-metal contact between a length of metallic conduit and a conduit coupling, the metal-to-metal contact between an equipment enclosure and structural steel or, a bond may consist of a separate jumper wire between enclosures because the physical configuration between enclosures to be electrically joined does not provide an adequate low impedance connection.

The Code permits the use of non-metallic enclosures for power conductors such as non-metallic conduit and non-metallic sheathed cable under certain conditions. However, general practice in a test facility would be to use metallic enclosures over insulated power conductors such as metallic conduit, armored cable or sheet metal wireway.

All metallic mating surfaces and connecting hardware must be constructed of galvanically compatible metals, see Table 2-3. When a more noble metal is joined to a less noble metal, electro-chemical corrosion will occur. This simple battery

Corroded end (anodic,	18-8 Stainless (active)	Silver solder
or least noble)	18-8-3 Stainless (active)	Nickel (passive)
Magnesium	Lead-tin solders	Inconel (passive)
Magnesium alloys	Lead	Chromium-iron (passive)
Zinc	Tin	18-8 Stainless (passive)
Aluminum 2S	Nickel (active)	18-8-3 Stainless (passive)
Cadmium	Inconel (active)	Silver
Aluminum 17ST	Brasses	Graphite
Steel or Iron	Copper	Gold
Cast Iron	Bronzes	Platinum
Chromium-iron (active)	Copper-nickel alloys	Protected end (cathodic,
Ni-Resist	Monel	or most noble)

Note: Groups of metals indicate they are closely similar in properties.

TABLE 2-3
Position of Metals in the Galvanic Series

cell action produces a high corrosion rate on the less noble metal, while the more noble metal remains un harmed. Also, coating of the noble metal with its less noble counterpart will result in mechanical weakness as well as a high impedance joint. In fact, a rectifier of sorts is formed creating all of the problems relative to harmonic generation.

Metallic mating surfaces which are susceptible to oxidation must be protected by application of a protective coating around the entire periphery of the mating surfaces. The electrical impedance offered by oxide films formed over an extended period of time can be quite significant relative to overall design impedance of the grounding system.

Electrical connections between metallic mating surfaces must be implemented in order to realize a rigid and low impedance contact. Some of the more important mechanical considerations are as follows:

a. Mating surfaces of metallic members should be welded or brazed around the entire periphery of the contacting area in all cases where possible and practical.

b. In lieu of welded or brazed connections, bolted sections may be used. Bolted sections must be implemented to insure: (1) a consistant contact pressure over an extended period of time; (2) minimal crevice area around metallic mating surfaces; and (3) a high resistance to atmospheric corrosion over an extended period of time. It is recommended that palnuts be used to maintain a permanently tight joint.

c. Rivets should not be used as an electrical connection on metallic members subjected to fluctuations in stress or strain or minute movements of the bond connections.

d. Protective or non-conducting coatings must be removed from the contact area of all mating surfaces before the bond connection is made.

2.2.6 COMMON-MODE VOLTAGE

A common-mode voltage - a voltage appearing on each line of a two conductor signal wire and a common reference point, usually the system ground - can result from many sources such as electrostatic fields, inductive fields, ground potentials differences, etc. It is important to note that a common-mode voltage is a voltage which appears between each signal wire and the common ground (see Figure 2-50).

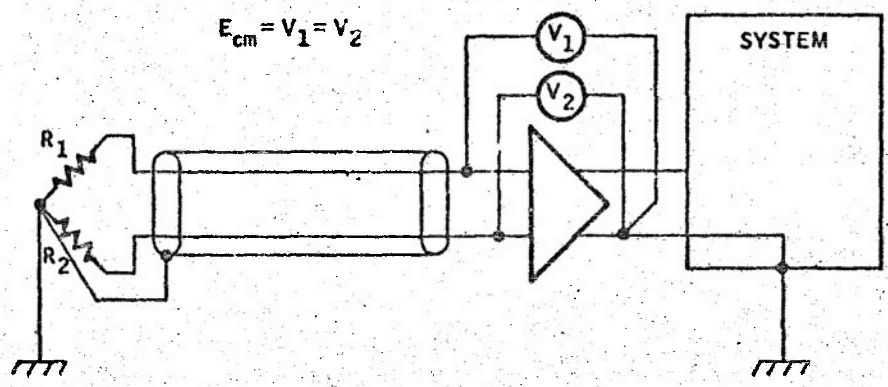


FIGURE 2-50
Common-Mode Voltage

Although this common-mode voltage appears at the input to the differential amplifier, the amplifier will only amplify the difference voltage between the two input wires. Thus, the output of the amplifier will be zero volts if $V_1 = V_2$. This is often not the case since in some transducers such as thermocouples R_1 and R_2 are not equal because of the wire or transducer resistance variations. A certain fraction of the common-mode voltage is therefore converted through the impedances in the signal line and the unbalance impedances of transducers into a normal-mode voltage. This conversion is commonly called common-mode-to-normal-mode conversion. The normal-mode voltage is the voltage which appears between the signal wires only. A measure of a circuit or amplifiers ability to reject this conversion is called the CMR (Common Mode Rejection) ratio. The CMR

ratio is defined as the ratio of the common-mode voltage (E_{cm}) to the resultant converted normal-mode voltage (E_{nm}).

In high quality instrumentation differential amplifiers the CMR of the amplifier input circuit is generally one million to one at DC to 60 cycles AC. In most cases, CMR will decrease in magnitude as the frequency of the common-mode voltage increases. The reason for this is due to the impedance of the coupling which is inversely proportional to frequency. CMR values for data input systems are often less than one million to one by a factor of two or three because multiplexers and other input circuitry will tend to degrade system performance due to the presence of capacitance in connectors and switches external to the amplifier.

The common mode to normal mode conversion should be analyzed further in order that effective measures may be taken to increase the CMR of an instrumentation circuit or circuits. The conversion process varies in accordance with the individual parameters of each instrumentation system such as line unbalance, length of instrumentation cable, type of shielding, etc.. However, the conversion process can be approximated by a lumped parameter system as shown in Figure 2-51.

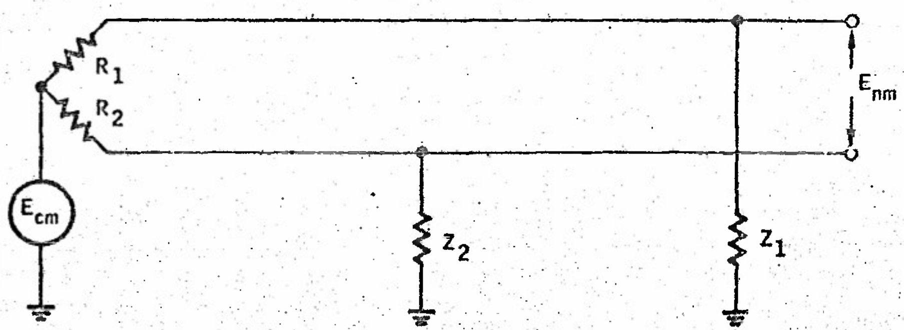


FIGURE 2-51
Common-Mode to Normal-Mode Conversion Equivalent Circuit

R_1 & R_2 = lumped line resistances plus any transducer unbalance

Z_1 & Z_2 = leakage impedances to ground

For ease of analysis, Figure 2-51 can be redrawn as shown in Figure 2-52.

$$E_{nm} = E_{cm} \left(\frac{Z_1}{R_1 + Z_1} - \frac{Z_2}{R_2 + Z_2} \right)$$

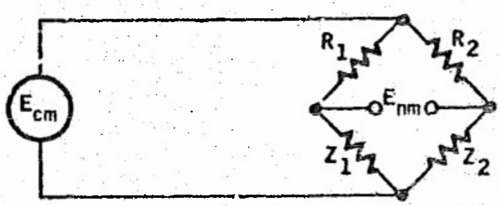


FIGURE 2-52
Simplified Common-Mode to Normal-Mode Conversion

As defined earlier the common-mode rejection ratio is a ratio of common-mode voltage, E_{cm} to the resultant normal-mode voltage, E_{nm} or

$$CMR = \frac{E_{cm}}{E_{nm}} = \frac{(R_1 + Z_1)(R_2 + Z_2)}{Z_1 R_2 - Z_2 R_1}$$

From observation of this equation it can be seen that the CMR can be increased by making the denominator approach zero, $Z_1 = Z_2$ and $R_1 = R_2$. Since $R_1 = R_2$ is difficult to realize in a real system, a more realistic solution would be to make the leakage impedances much larger than R_1 and R_2, assuming $Z_1 = Z_2 = Z$ then CMR is

$$CMR = \frac{R_1 R_2 + R_1 Z + R_2 Z + Z^2}{Z(R_2 - R_1)}$$

Since $Z^2 > (R_1 R_2,\ R_1 Z,\ R_2 Z)$

Then CMR $\frac{Z}{(R_2 - R_1)}$

Therefore the larger the leakage impedance and the smaller the unbalance impedances of the line the greater will be the CMR.

The most practicable method of obtaining a high leakage impedance is the use of shielded instrumentation cable which has a shield coverage efficiency of 100% (see Figure 2-53). A typical copper braid shield has a shield coverage of about 90 to 95%. Copper wrap shields offer a slightly higher coverage but after the cable has been mechanically distorted this coverage falls off rapidly. The aluminum foil type shielded cable provides the best shield coverage available today. 100% coverage is possible with the foil shields. Care must be taken in buying and specifying foil shielded cable to insure that sufficient overlap of the foil shields is given so that no discontinuities will occur in the shield coverage. A 50% overlap should be specified as a minimum. Table 2-4 illustrates a general comparison of braided shield cables and foil shielded cables.

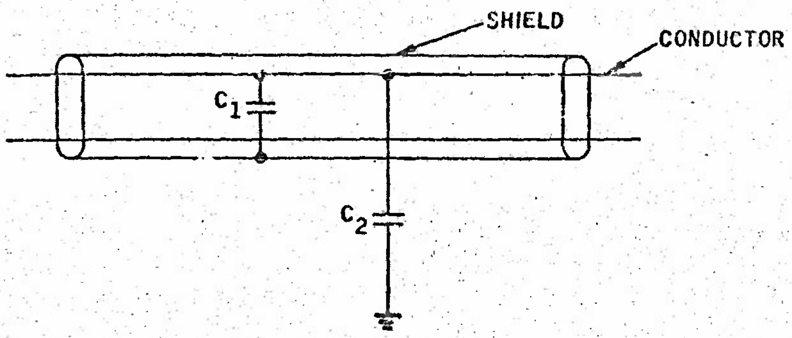


FIGURE 2-53
Shielded Instrumentation Cable

Assume copper braid shield coverage = 90%

then wire-to-shield capacitance = C_1 = 50 pf/FT

and wire-to-ground leakage capacitance = C_2 = 5 pf/FT

2.2.7 LINE BALANCING

As explained in the previous section a normal-mode voltage converted from a common-mode voltage will not usually be rejected by an instrument because it recognizes the normal-mode voltage as signal information. Therefore, the conversion of common-mode voltage to normal-mode voltage must be prevented. This form of conversion is a particularly difficult one to cope with because it is common for unshielded thermocouple extension wires to be run in conduit where the capacitive coupling from wire to conduit is quite high. The wire to conduit capacitance has been measured as follows:

(Using 22 gage I.C. duplex parallel in conduit)

One pair in 1/2 inch conduit, each wire to conduit = 0.0015 f/100 ft.

One pair to 30 pairs in 3/4 inch conduit, each wire = 0.0030 f/100 ft.

A good isolation transformer = 0.1 pf

Since each extension wire has a different resistance, the phase shift and attenuation in each wire will be different. Therefore, a signal difference between the wires will appear as an input signal to the load circuit or amplifier. Table 2-5 gives the resistance unbalance that exists between the extension wires of most common thermocouples.

	AWG	AWG Drain Wire	Shield % Coverage	Cap. pf/FT	Leakage Cap. pf/FT	Shield Resistance ohm/1000 Ft	Contact Resistance of Foil to Drain
Aluminum Foil Shield	22	18	100	77 Wire-to-shield	.008	16	0./ohm/FT
Copper Braid Shield	22		90	72 Wire-to-shield	.017 pf	6.0 s	

TABLE 2-4

Typical specifications of Shielded Cables for Three Conductor Cable

Type	Ohms/100 FT (20 gage)	Resistence Ratio	For resistive balance: Wire Gage	Diameter (in.)
Copper/ constantan	1.015 28.71	28:1	20 6	0.032 0.162
Iron/ constantan	6.225 28.71	4.6:1	20 13-14	0.032 0.06-0.07
Chromel/ alumel	41.59 17.32	2.4:1	16-17 20	0.04-0.05 0.032
Chromel/ constantan	41.59 28.71	1.45:1	20 18	0.032 0.040

TABLE 2-5

Thermocouple Extension Wire Resistence Data

As an example consider 1,000 feet of 20-gage, single pair copper/constantan extension wire run in 1/2 inch conduit with a one volt RMS common-mode voltage. From the previous section,

$$CMR = \frac{Z}{R_2 - R_1} = \frac{E_{cm}}{E_{nm}}$$

therefore

$$\frac{E_{nm}}{E_{cm}} = \frac{R_2 - R_1}{Z} = \text{Common-mode to normal-mode conversion factor}$$

R_1 = Copper = 10.15 ohms/1000 feet

R_2 = Constantan = 28.71 ohms/1000 feet

$R_2 = R_1 = 277$

$$Z = \frac{1}{2\ fc} = .1733 \times 10^6 \text{ ohms at 60 CPS}$$

$$E_{cm} = 1 \times 2.8 \text{ V peak-to-peak}$$

$$E_{cm} = (2.8) \quad \frac{277}{.1732 \times 10^{-6}} = 4.4 \times 10^{-3} \text{ V p-p}$$

Now consider the chromel/constantan couple which has the smallest unbalance of the most common thermocouples. Using the same conditions as before

$$\frac{E_{nm}}{E_{cm}} = \frac{R_2 - R_1}{Z}$$

R_1 = Chromel = 415.9 ohms/1000 feet

R_2 = Constantan = 287.1 ohms/1000 feet

$R_2 - R_1 = 129$ ohms

$$Z = \frac{1}{2\ fc} = .1733 \times 10^{-6}$$

$$E_{cm} = 1 \times 2.8 = 2.8 \text{ V peak-to-peak}$$

$$E_{nm} = \frac{2.8\ (129)}{.1733} \times 10^6 = 2.08 \times 10^{-3} \text{ V p-p}$$

Thus, the smaller the difference between thermocouple wire resistance the less common-mode to normal-mode conversion will occur. One way of obtaining a close balance between thermocouple wires is to use a smaller gage wire for the low resistance wire (copper, iron, chromel) and use a much larger gage wire for the higher resistance wire (constantan). If twisted thermocouple wire is used the wire sizes must be selected with care, since twisting two wires of considerable difference in size is difficult and often impractical.

As described in Para. 2.2.2 the conduit should be connected to earth ground at the transducer end in order to reduce the wire to conduit capacitance. If the conduit is isolated from earth except at the transducer ground point, the wire to shield capacitance can be greatly reduced making Z much larger thereby reducing the normal code conversion voltage E_{cm}.

Balancing lines beyond the transducer may also be given consideration. If differential input decives are used, balanced lines are a must. To demonstrate the effects of balancing on a typical instrumentation cable, external capacitors were added to each signal wire to ground. Each capacitor was varied until a minimum noise signal was obtained on a scope with a differential type plug-in amplifier. Two configurations were tested; no unbalance at transducer end and with 1000 ohms unbalance at the transducer end. The tests showed that no significant

improvement could be made in reducing noise levels in the balanced transducer configuration and that an improvement ratio of 10 to 1 was observed in the unbalanced transducer configuration when a balance condition was approached.

From the previous section, an equivalent circuit of a typical lumped parameter instrumentation line will reduce to a wheatstone bridge type configuration, as shown in Figure 2-54.

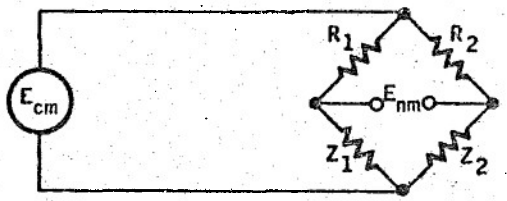


FIGURE 2-54
Equivalent Circuit of a Lumped Parameter Instrumentation Line

The equation describing this circuit was given as:

$$E_{nm} = E_{cm}\left(\frac{Z_1}{R_1 + Z_1} - \frac{Z_2}{R_2 + Z_2}\right)$$

The impedance factors,

$$\frac{Z_1}{R_1 + Z_1} \quad \text{and} \quad \frac{Z_2}{R_2 + Z_2}$$

determine the balance or unbalance of the line. Thus, since R_1 and R_2 represent the lumped wire and transducer impedances it can be seen that a careful selection of wire sizes will significantly effect the amount of balance in the line. Also, Z_1 and Z_2 can be controlled to some degree by using low capacitance patch boards, terminal strips, low leakage capacitance cables, and very high input to earth impedance recording devices were possible. If these two impedance factors can be made equal then, theoretically E_{nm} will be zero. This is almost an impossible situation. However, very small unbalances are possible in certain situations such as thermocouple transducers.

2.2.8 FILTERING

Filtering may be used advantageously in instrumentation systems to reduce unwanted higher frequency components from power or signal line inputs.

2.2.8.1 Power Line Filtering

Noise can be coupled into power lines by either of two modes; (1) transformer, or (2) common-mode (capacitive). Figure 2-55 illustrates the two types of coupling.

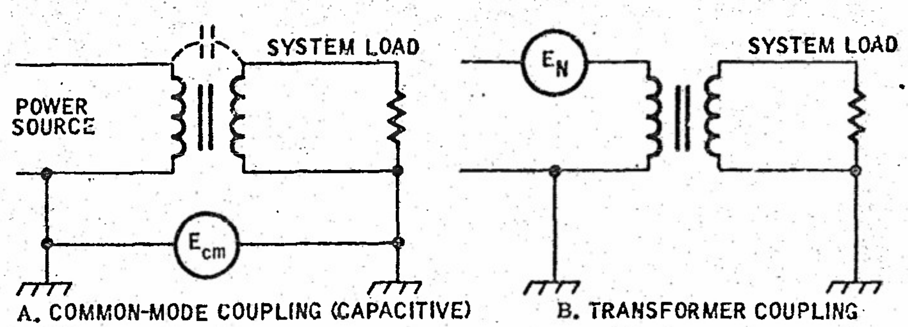


FIGURE 2-55

Two Methods of Noise Coupling Into Power Lines

In Figure 2-55A noise is coupled capacitively from primary to secondary. Shielding, as described previously, is used to diminish this coupling probelm and reduce ground loop caused noise.

Figure 2-55B shows another method of noise energy coupling; magnetically through the transformer just as the power energy is coupled. Shielding will not, and obviously should not, prevent this type of energy transfer.

Unwanted frequencies which are direct coupled can result from power source noise developed at the power source or by feedback back into the line from machinery, electrical, or electronic devices to which the line provides operating power. The most effective means for reducing direct coupled noise is the employment of line filters.

There are two possible ways to handle power line filtering depending on the type and source of the noise signal. In general, it would be best to eliminate any possible sources of noise. Power line filters should be used on all equipment which involves the switching of inductive loads, rotary machinery, etc. Within the instrumentation equipment itself sources of noise are frequently high current DC power supplies to transfer the impulse created by switching on the secondary of the input power transformer back to the AC power line. Also troublesome can be equipment such as typewriters, punches, etc.

Power line filters should be located as close to the noise generating equipment as possible. This equipment should be designed to prevent noise from being generated. Filtering may also be used on the incoming power lines to the system to reduce any noise remaining after source line filters are installed.

Two types of filters are commonly used for power line filtering; (1) the T filter and the, (2) Pi network. The Pi network illustrated in Figure 2-56 provides a higher roll-off rate than the T network; however, it frequently produces "ringing" or oscillations when impressed with an impulse. The Pi network should generally

be used where the noise signal is rather periodic in nature such as interference from a radio transmitter, etc.

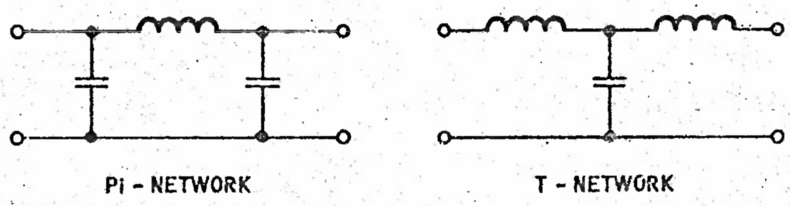


FIGURE 2-56
Filters

Although T network, does not provide as high a roll-off as the Pi network, it is usually sufficient for filtering of impulse type noise sources, such as the power supplies previously mentioned and is not subject to the oscillation that the Pi network frequently exhibits.

Each of the filters discussed above can be used in two possible configurations, as illustrated in Figure 2-57. In general, the single leg configuration is sufficient for most system applications. Where balanced three-phase power is used, the double-leg configurations should be used. Where filtering is employed at the source of the noise the balanced network as illustrated in Figure 2-58 may be used. However, use caution in grounding these filters at the load end of the power line since this could cause heavy AC power current to flow in the ground system. The balanced network is always used at the source of three-phase power systems.

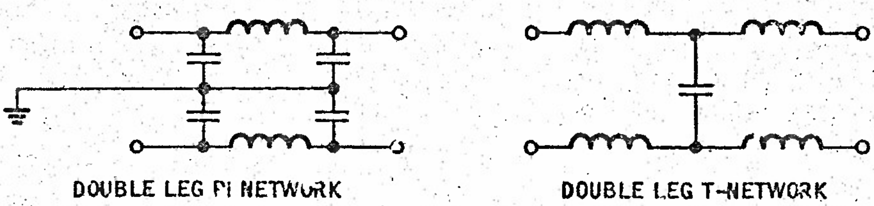


FIGURE 2-57
Double Leg Networks

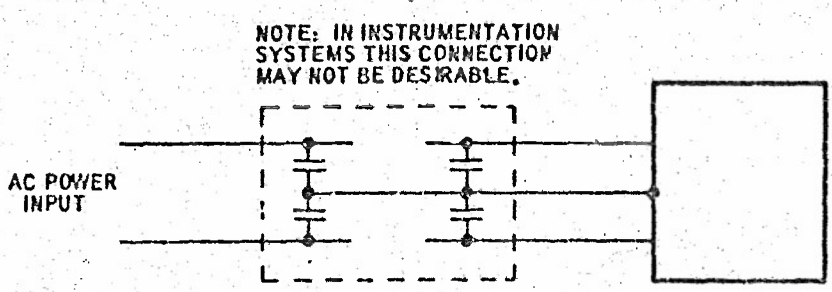


FIGURE 2-58
Balanced Network

2.2.8.2 Signal Filtering

Signal filtering may be employed whenever the unwanted noise frequency is outside the frequency band of the data of interest. Generally, signal filtering may be accomplished at two locations depending on type of system in use. Where amplifiers are used in each data channel, the filtering can take place at the output of the amplifier. This provides filtering not only of the data signal itself but also of any high frequency common-mode voltage that may be present at the input of the amplifier.

In systems that do not employ an amplifier for each data channel, such as systems using low level commutators, filtering must be employed at the input of the commutators.

Some special considerations which should be made in using filters with commutated A/D data acquisition systems are given below:

a. Filters placed at output of commutator can cause rounding off of the "PAM" output wavetrain if filtering is too severe. Data noise will be filtered, however, data levels themselves may be adversely affected.

b. Filters placed at the commutator input may cause error in the data by inter-action between the filter capacitance and the commutator input capacitance. This error is called charge sharing and will be minimum only if the filter capacitance is either very large or very small in relation to the commutator input capacitance. It is considered good practice to isolate the commutator from the filter by active isolation circuitry. This measure will eliminate the charge sharing affect.

c. A filter which is connected directly to the output of a transducer may cause adverse loading of the transducer. Also, the filter characteristics may be adversely affected by changes in transducer impedance. To avoid these problems it is recommended that active buffering be placed between transducer and filter. The transducer-filter and filter-commutator interactions can be eliminated by using buffered filtering. A buffered filter can be connected within a differential amplifier in such a manner that neither the transducer nor the commutator are directly connected to the filter.

2.2.9 AMPLIFIERS

There are two primary types of instrumentation amplifiers used in data systems, the floating single-ended DC amplifier and the guarded isolated differential DC amplifier. Other types of amplifiers used in instrumentation systems include AC coupled, bridge type differential, magnetic, and a wide range of special purpose amplifiers which are usually related to a specific type of transducer or signal conditioning technique. Descriptions of the more common instrumentation amplifiers and a partial summary of amplifier characteristics are discussed in the following paragraphs.

The single-ended amplifier does not provide input circuit to output circuit isolation. That is, the "low" signal side of the input to the single-ended amplifier is electrically common to the "low" signal side of the output.

While the single-ended amplifier is normally considered to have no common-mode rejection (CMR) capability, there is a limited circuit configuration which may provide some degree of CMR (See Figure 2-59).

The load leakage impedance (Z) completes the path for the common-mode current (I_{cm}) which flows through the source resistance, line resistance, and low side of the single-ended amplifier. The larger Z is, the larger will be the CMR capabilities of the circuit. If Z_A is very large, then the normal mode error voltage E_{nm} caused by E_{cm} which appears across the amplifier input is:

$$E_{nm} = \frac{E_{cm}\ (R_S + R_L)}{R_S + R_L + Z} \approx \frac{E_{cm}\ (R_S + R_L)}{Z}$$

The common-mode rejection is therefore:

$$CMR \approx \frac{Z}{R_S + R_L}$$

The load must be floating, such as a galvanometer, and the leakage impedance Z must be very large to reduce the error voltage. The common-mode rejection then is actually a function of the system circuit configuration and not the amplifier.

The same situation exists if the load is grounded, and the leakage impedance Z is at the floating signal source. The balanced bridge amplifier, as seen in Figure 2-60, depends on maintaining a balanced input through the upper and lower signal paths (DC and AC) in the amplifier for common-mode rejection. Maintaining a balanced line is difficult when using long lines and variable resistance transducers.

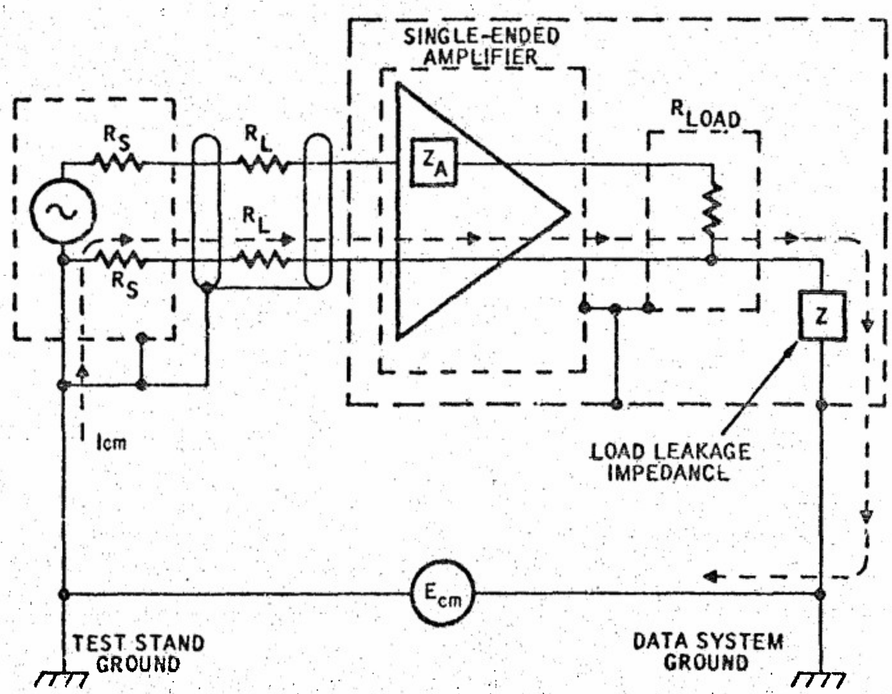


FIGURE 2-59

Common-Mode Rejection with the Single-Ended Floating Amplifier and Floating Load

Figure 2-61 illustrates the need for complete balance in both legs of the bridge amplifier. When balanced, I_{cm_1} and I_{cm_2} are equal and the normal-mode voltages generated by the various impedances balance out. Any unbalance in R_S, R_L, R_{in}, R_F, or Z_L will result in nomal-mode voltages due to E_{cm}.

The stability, bandwidth, and gain of a high quality bridge amplifier may be quite high. However, noise may be relatively high and the maximum common-mode voltage permitted at the input is considerably lower than that of the isolated differential DC amplifier.

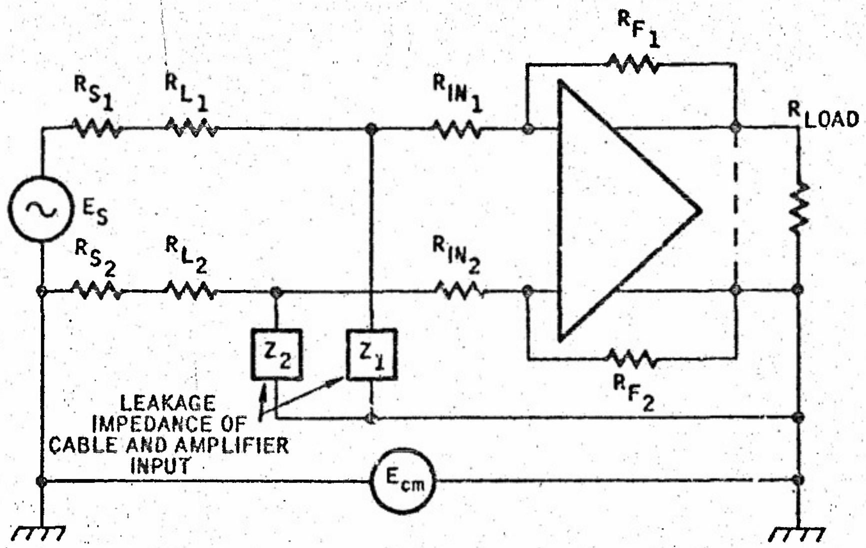


FIGURE 2-60
Balanced Bridge Differential Amplifier

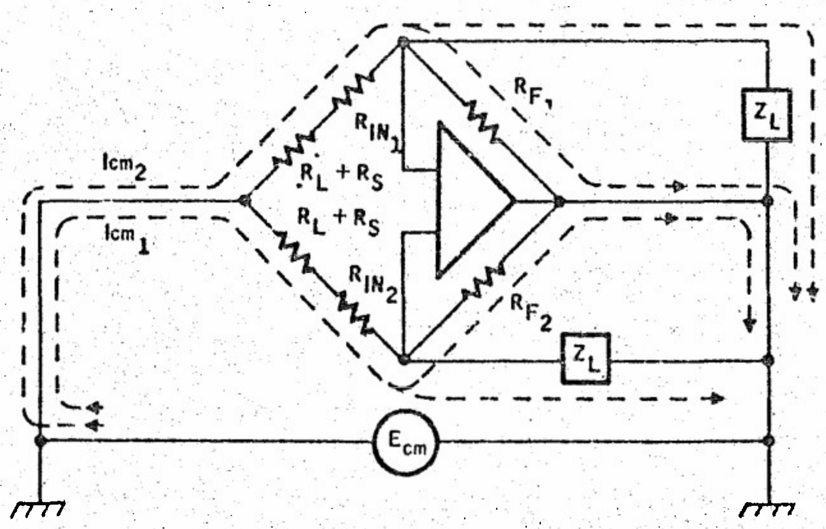


FIGURE 2-61
Common-Mode Rejection in the Bridge Amplifier

2.2.9.1 Single-Ended Amplifiers

In many DC instrumentation systems wideband single-ended amplifiers are used because of their superior wideband capability as compared to the chopper type DC amplifier whose maximum practical bandwidth is 10 KC. Since the input ground circuit is common to the output ground circuit in a single-ended amplifier it does not have capabilities for common-mode rejection. When using a single-ended amplifier, care must be taken in order that ground loops are not formed between instrumentation channels and between test stand areas. In Figure 2-62 is shown two bridge transducer channels which have single-ended wideband amplifiers on the output of each transducer. The dashed line indicates the ground loop which is formed by improper instrumentation design. To prevent this ground loop, the two channels can be supplied with individual isolated DC excitation power supplies as shown in Figure 2-63.

If grounded transducers are being instrumented, and the data will be recorded directly as an analog signal by an oscillograph or a strip-chart recorder, the use of single-ended amplifiers could cause ground loop noise caused by common-mode generators in two different areas of the system as shown in Figure 2-64. Common-mode voltage E_{cm1} is caused by two ground connections to earth at widely separated points and common-mode voltage E_{cm2} is caused by a temperature gradient along the test specimen to which the thermocouples are bonded. The ground loop currents around the loops are shown in dashed lines. Actually E_{cm2} will be a combination of temperature gradient (thermocouples) along the test specimen and ground loop current from E_{cm1} through the impedance separating the two thermocouples. Figure 2-65 shows an improvement which can eliminate the largest of the two common-mode voltages. All grounds at the recorder end are connected to an isolated copper ground plate. The copper ground plate is grounded at the test specimen ground through a large insulated copper ground wire of size number 2/0 AWG to number 4/0 AWG. This grounding procedure then removes the earth common-mode voltage (E_{cm1}) entirely because only one connection to earth ground has been established. The remaining common-mode voltage E_{cm2} is a much smaller value and in most direct recording methods will not add significant error to the data measurement.

When greater data accuracies and more channels are desired, the usual approach is the use of a digital data acquisition system which can process and record the information on several hundred channels in rapid sequence. To illustrate the use of single-ended amplifiers and the grounding procedure of single-ended amplifiers in such a system refer to Figure 2-66. Only two channels of a digital data acquisition system are shown in this configuration. The transducers are bonded

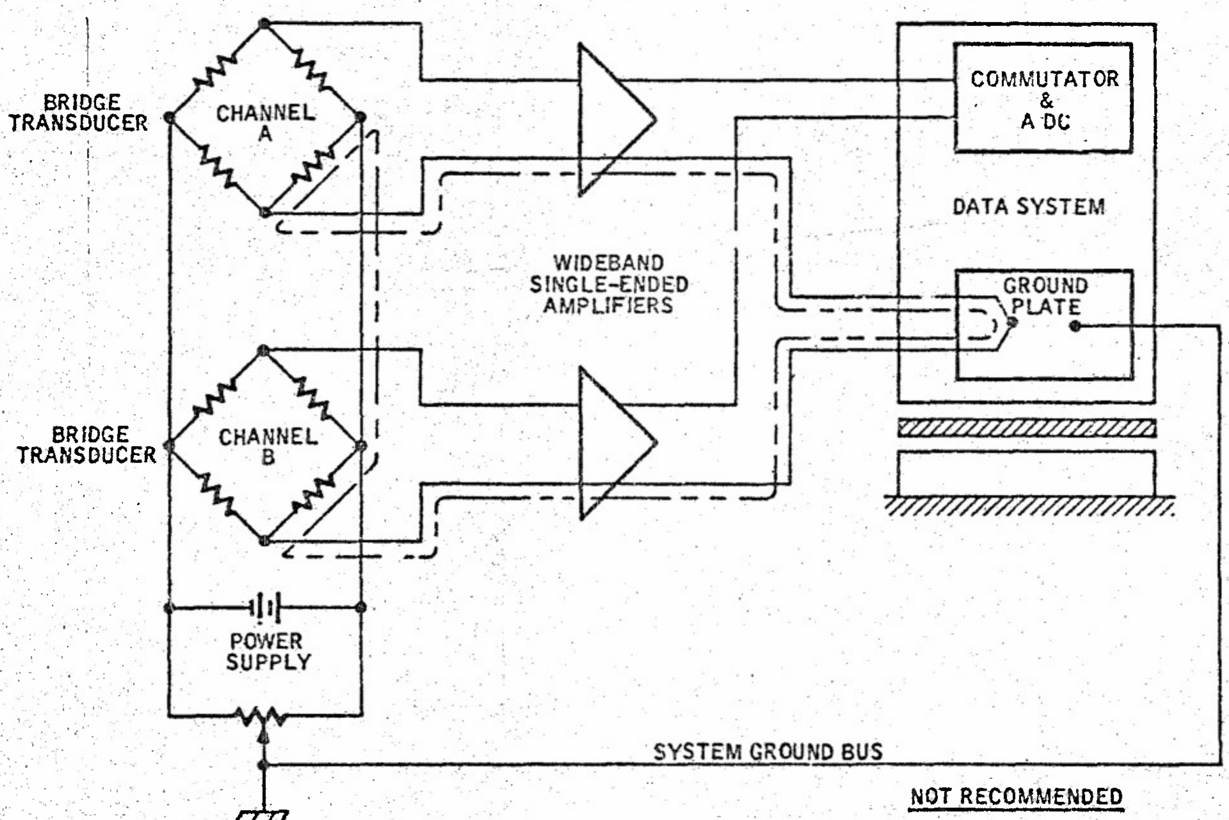


FIGURE 2-62
Two Channels of 4 Arm Bridge Circuits
Showing Ground Loop Circuit Caused by Single-Ended Amplifiers

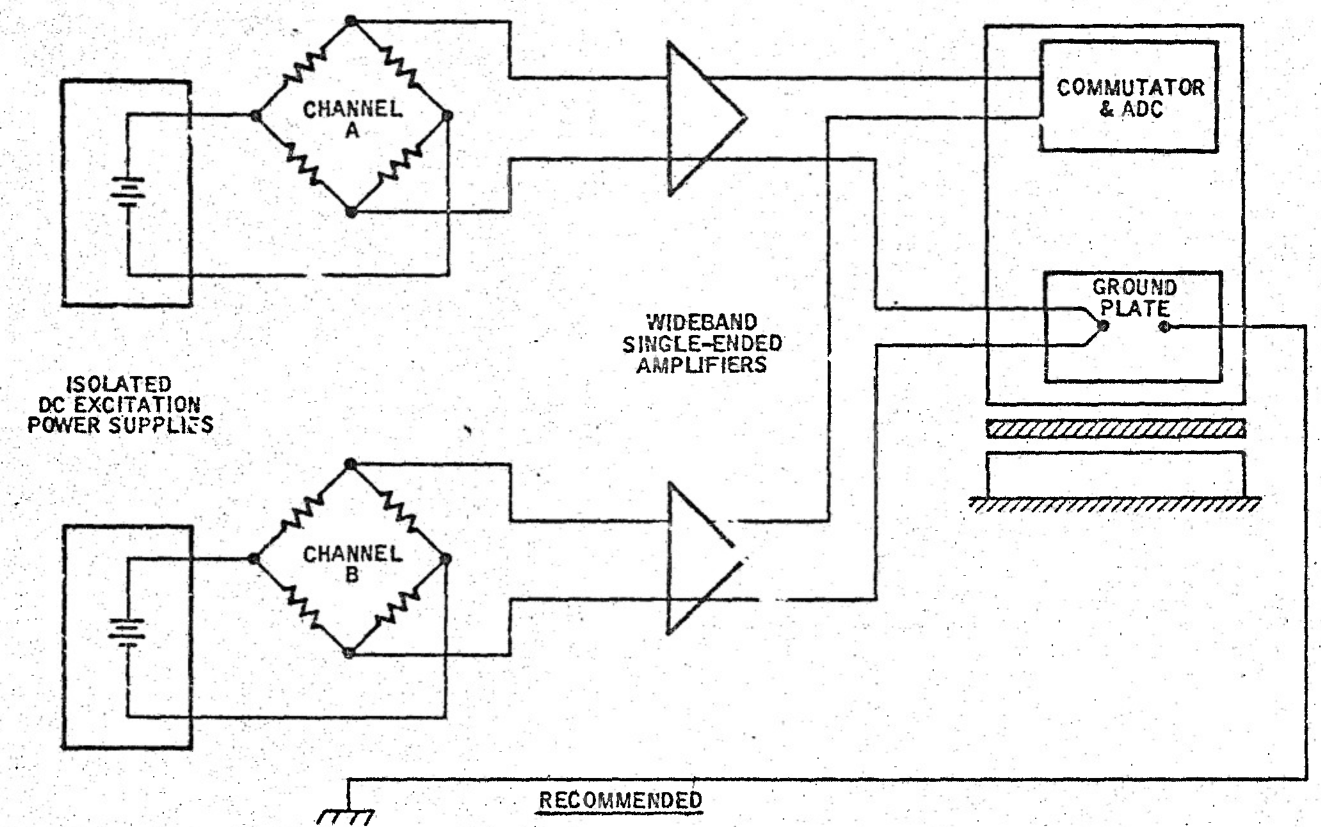


FIGURE 2-63
Two Channel 4 Arm Bridge Circuits
Showing Use of Isolated DC Power Supply to Prevent Ground Loops

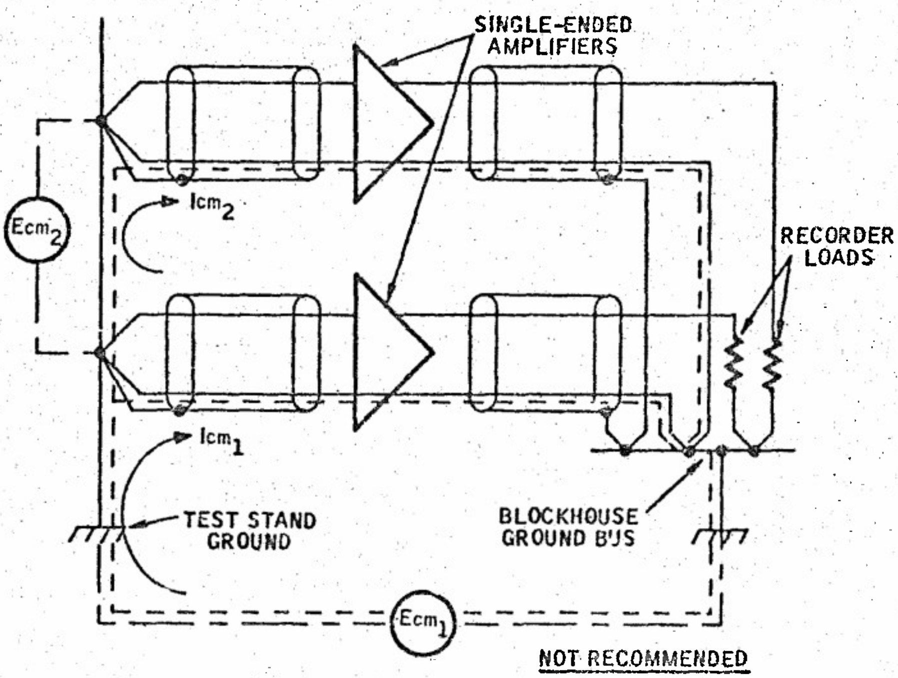
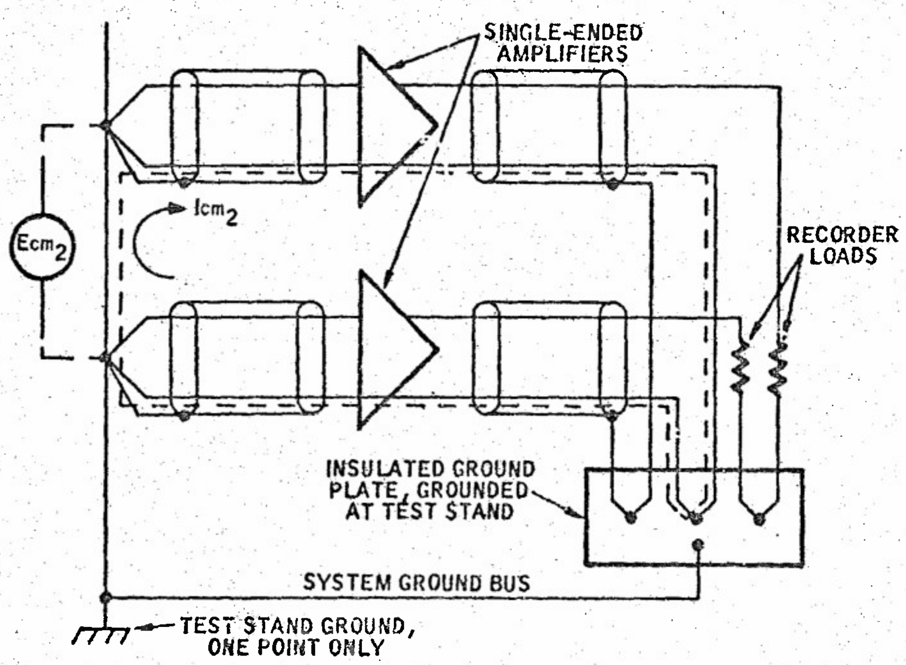


FIGURE 2-64
Two Channel Thermocouple Instrumentation
Using Single-Ended Amplifiers and Blockhouse Ground

thermocouples and the ground bus principle is adhered to in order to eliminate the earth common-mode voltage. The thermocouples are connected to the inputs of single-ended amplifiers. Each amplifier output is then connected to a three pole switch. The switches are controlled by the digital system which automatically selects the one switch to be closed so that the data from that particular channel may be processed. It can be seen that the switches which make up the commutator accomplish the necessary channel isolation in eliminating any ground loops between channels.

Notice that the input cable shields are connected at the transducer and are not carried through the amplifier and that a three pole switch configuration in the commutator provides channel isolation across all instrumentation wires.

This type of digital acquisition system is quite expensive because of the amplifier in each channel input cable. If a low-level type commutator were used in place of the high-level commutator, the requirement for an amplifier in each channel can be changed to a single amplifier for several channels. In a system with several channels being sequenced (commutated) at a fast rate then it is possible to utilize a second level of commutation in such a way that the data channels are grouped



NOT RECOMMENDED

FIGURE 2-65

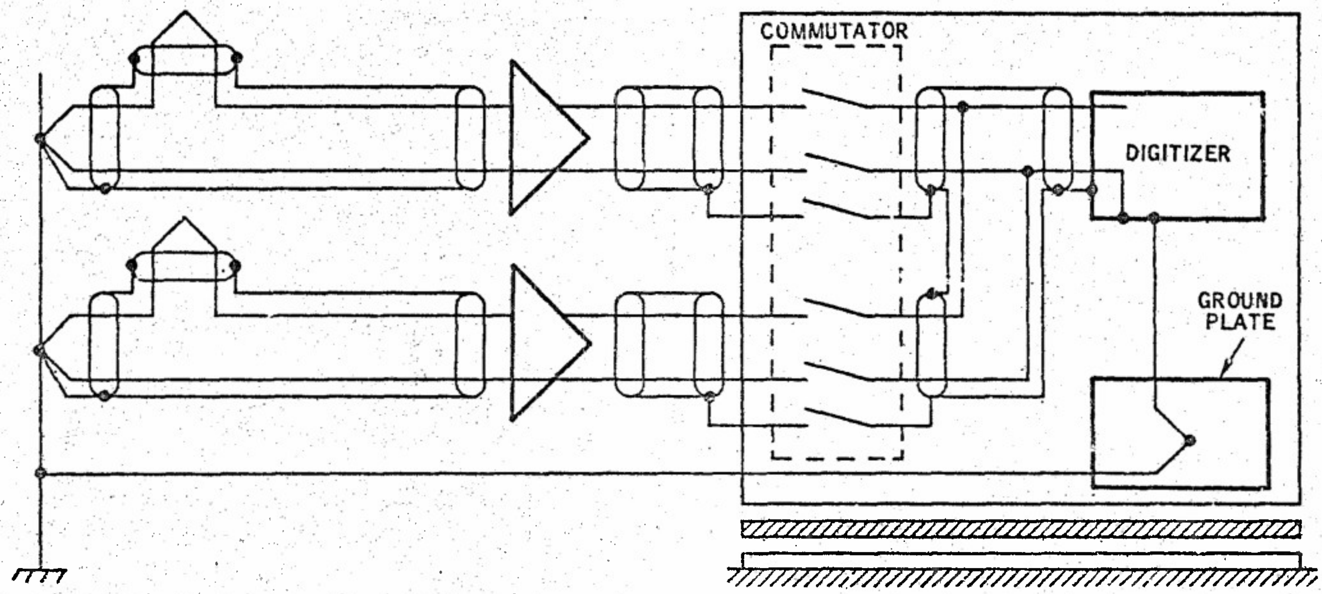
Two Channel Thermocouple Instrumentation Using Single-Ended Amplifiers and Insulated Ground Plate in the Instrumentation System

together and each group of data channels share a single amplifier which lowers the cost even further. A two channel system is illustrated in Figure 2-67.

When using single-ended amplifiers with thermocouples as mentioned above it must be remembered that channel-to-channel isolation is required for proper operation in an uncommutated tape system. If the output of the single-ended amplifier is driving a floating load such as a galvanometer then channel-to-channel isolation is accomplished. However, single-ended recorders will short all channel grounds together if commutation is not used. In other words to eliminate ground loops when using single-ended amplifiers some form of channel-to-channel isolation must be used, commutation, floating load or isolation transformers in the signal line.

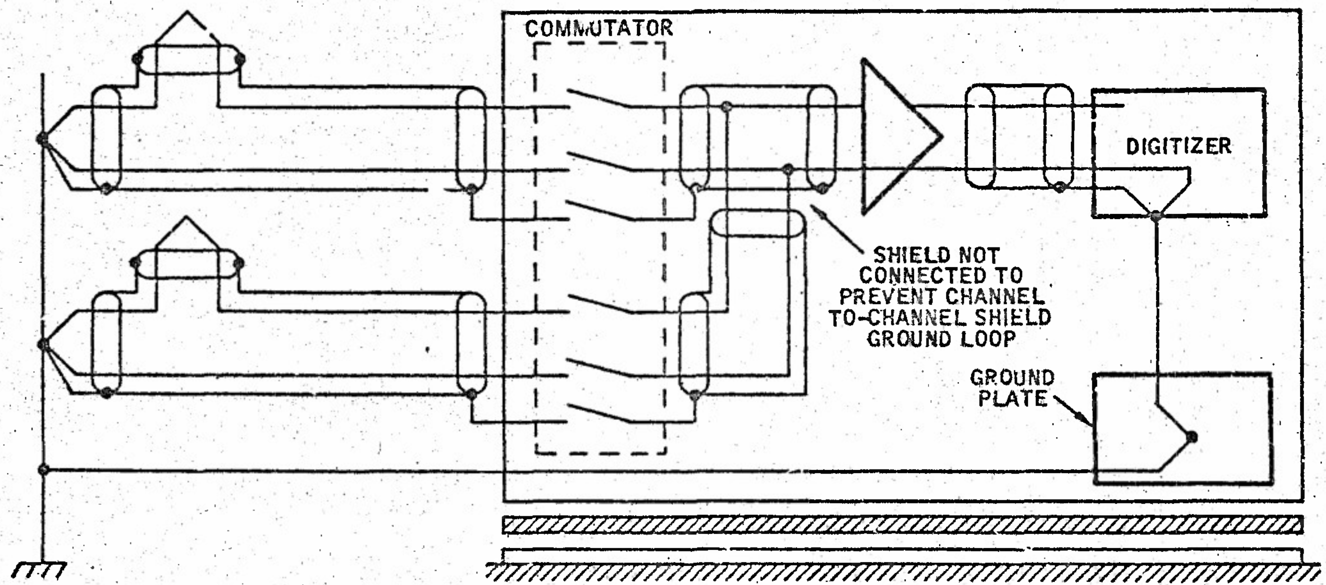
2.2.9.2 Isolated Differential Amplifier

The most versatile amplifier in instrumentation systems is the isolated differential amplifier. Two versions of the isolated differential amplifier are shown in Figures 2-68 and 2-69. Each type has a guard shield surrounding the input section of the amplifier.



RECOMMENDED

FIGURE 2-66
Digital Data Acquisition System Using Single-Ended Amplifiers Before High-Level Commutator



RECOMMENDED

FIGURE 2-67
Digital Data Acquisition System Using Low-Level Commutation and Single-Ended Amplifiers into Digitizers

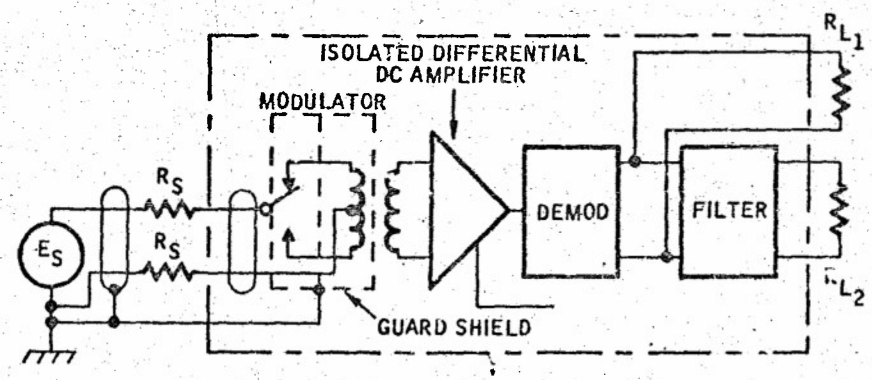


FIGURE 2-68
Chopper Input Isolated Amplifier

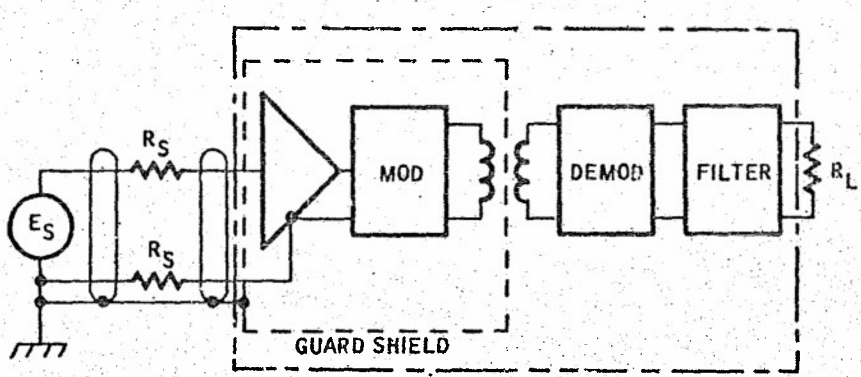


FIGURE 2-69
Isolated Type Differential Amplifier

Common-mode rejection in the guarded isolated differential amplifier is dependent on the quality of the guard shield. This type of amplifier can stand a certain amount of unbalance at the input and still maintain good CMR. The amplifier CMR is often specified at from 350 to 1000 ohms unbalance at the input. Figure 2-70 illustrates the common-mode rejection capability of an isolated differential amplifier.

The leakage impedances Z_1 and Z_2 may be internal or external to the amplifier. The difference in line resistance is normally negligible when compared to the 1000 ohms unbalance at the signal source. Also, since Z_1 and Z_2 are almost equal, the common-mode current I_{cm_1} and I_{cm_2} will each develop approximately

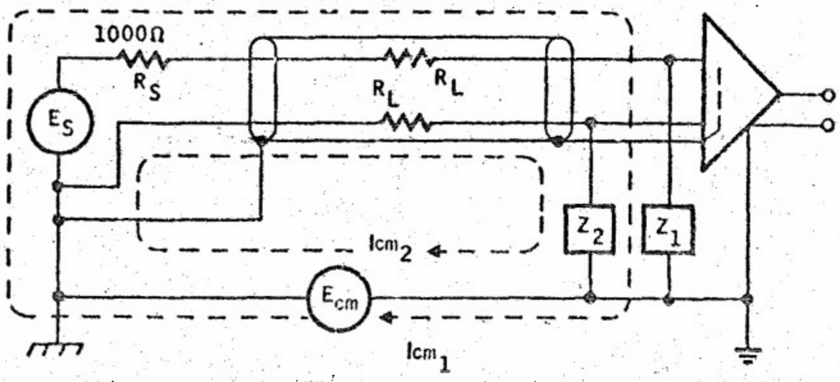


FIGURE 2-70

Common-Mode Rejection in the Isolated Differential Amplifier

equal potentials across each input line impedance, causing a common-mode voltage at the amplifier input. However, the 1000 ohm unbalance, R_S, will cause a further voltage drop (common mode-to-normal mode conversion) in one line will not be a part of the common-mode voltage, but will appear to be a normal-mode or signal voltage to the amplifier. The normal-mode error voltage due to the common-mode to normal-mode conversion will be generated primarily in the line unbalance R_S and is due to I_{cm}.

The normal-mode voltage E_{nm} at the input of the amplifier is:

$$E_{nm} \approx \frac{E_{cm} \cdot R_S}{Z_1}$$

The common-mode rejection (CMR) for an amplifier is described as:

$$CMR \approx \frac{Z_1}{R_S}$$

For a more detailed analysis of CMR refer to Appendix C.

At 60 CPS and 1000 ohms unbalance a common-mode rejection of 120 db would require that Z_1 by less than 2.7 picofarads.

The guarded input to the isolation amplifiers must be gounded properly in order that the common-mode rejection of the amplifier be maintained at its maximum value. Because the common-mode rejection also applies to the input networks and cables going to the amplifier, the common-mode rejection of these input circuits should be considered and grounded properly.

The common-mode rejection characteristics of the isolated amplifier will be only as good as the input circuits. Therefore, the most important thing to consider is the common-mode to normal-mode conversion in the input circuits. This conversion takes place when a common-mode voltage is allowed to be converted to a normal-mode (signal) voltage through leakage impedances in the cable and serves unbalance resistance in the input circuits. The guard shield of an isolation amplifier serves as an extension of the input cable shielding and should be connected to it as shown in Figure 2-71.

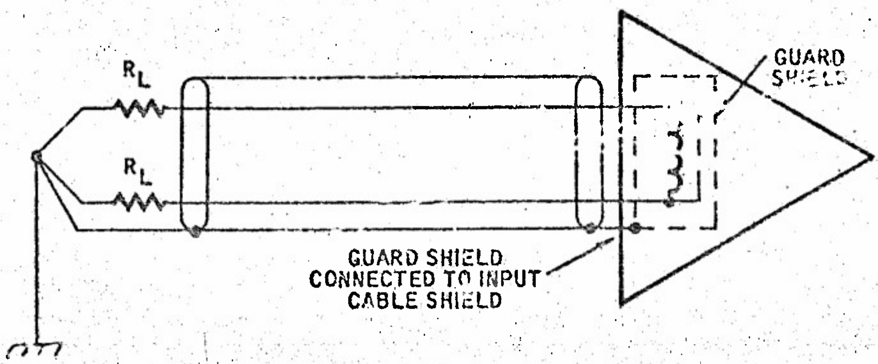


FIGURE 2-71
Guard Shield Connection of Isolated Differential Amplifier

If the guard shield is grounded at the amplifier input a potential difference will be established between the two ground points and the coupling capacitance from wire to shield in the cable will cause a common-mode to normal-mode conversion. With the guard shield of the amplifier connected to the input cable shield and the cable shield grounded at the transducer ground, the potential difference between signal wires and shields will be minimized thus increasing the capacitive impedance from shield to signal wire. This effectively increases the common-mode rejection of the input circuits since the impedance through which the common-mode error current must flow has been greatly increased.

The output guard shield of the isolated amplifier should be connected to the output cable shield. This connection provides an extension of the shielding of the output cable to the output transformer circuit of the amplifier. The chassis of the amplifier should be connected to the system ground plate for personnel safety.

Table 2-6 is a summary of the characteristics of the above amplifiers.

Type of Amplifier	Common-Mode Rejection	Maximum Number of System Grounds Advisable	Effects of System on CMR	Limits on Common-Mode Voltage
Single-Ended Grounded Output	None	1	----	None Allowed
Single-Ended Floating Output	See Text	1	See Text	High
Balanced Differential	Low 30-80 db	2	High	Low 5-15 Volts
Isolated and Grounded Differential	High 100-180 db	2	Low	High 200-300 Volts

TABLE 2-6

Amplifier Summary Chart

2.2.9.3 Amplifier Specifications

There is a lack of uniformity in amplifier specifications among the different manufacturers. Therefore, methods of testing will vary and often the published specifications will not mention limiting factors concerning performance. Frequently, the only way an engineer can be sure the amplifier he has selected will perform to requirements is to personally evaluate the amplifier. Usually the choice of an amplifier will be a compromise of features (including price) relative to the system requirements.

The amplifier specifications considered relative to the scope of this handbook are noise and common-mode rejection characteristics.

2.2.9.3.1 Noise

There are several types of noise inherent in all electronic equipment which limit the minimum signal levels that may be amplified. These include thermal noise, shot noise, and characteristic noise of tubes and transistors. These noise sources are considered independently and are usually given as a collective value for a given amplifier. The noise is considered random or "white" noise and the peak-to-peak amplitude will vary as a gaussian (normal) distribution. The noise is quite often specified as RMS and when measured as such must be measured with a power (watts) measuring instrument and not a peak reading RMS meter. However, in data systems the measurement accuracy will reflect the peak noise level in many cases. Since the noise is of a gaussian nature, the peak amplitude of the noise will randomly exceed several times the RMS noise value. Where noise is given as an RMS value, the peak noise amplitude (0 volts - to-peak volts) will be less than four times the RMS amplitude, 99.99 + % of the time. The peak noise amplitude will seldom exceed 10 times the RMS magnitude.

Definitions of the basic noise types are given below.

a. Johnson Noise

Johnson noise is the white noise voltage generated in a conductor due to thermal action upon free electrons within the conductor. The magnitude of noise relative to temperature, bandwidth of the measurement, and conductor resistance is:

$$(E\ noise)^2\ (RMS) = 4\ K\ T\ R\ B$$

where

K = Boltzmanns Constant or $1.374.10^{-23}$ joules per ^{O}K

T = Absolute temperature in degrees Kelvin

B = The frequency bandwidth under consideration

R = Real or resistive component of conductor.

This is part of the reason for the higher noise factor in amplifiers such as the balanced bridge type which have large resistances at the input stage.

b. Shot Noise

Shot noise is the product of random variations in current flow through any diode junction. The relationship for shot noise relative to the diode current is:

$$(i_{noise})^2\ (RMS) = 2\ e\ I\ B$$

where

i_{noise} = The RMS value of noise current

e = Coulomb change on an electron or $1.6.10^{-19}$ coulombs

I = Diode current in AMPS

B = Frequency bandwidth under consideration

As with Johnson noise the magnitude of shot noise is directly proportional to the frequency bandwidth involved.

Electron tubes are subject to shot noise as well as several other noise types unique to vacuum tubes and related to the physical configuration of the cathode, grids and also residual gasses. Tube noise is often defined in relation to an equivalent tube resistance with respect to the formula for Johnson noise. The equivalent resistance of a tube is part of the function of tube transconductance and the type of tube (i.e., triode, pentode, etc.). Therefore, tube noise can be analyzed as shot and Johnson noise and is directly proportional to bandwidth.

In addition to Johnson and shot noise, transistors exhibit an additional noise which is inversely proportional to frequency. This noise, often designated as 1/f (1/frequency) noise is therefore predominant at low frequencies and the magnitude of 1/f noise will vary with different types of transistors. Figure 2-72 outlines the characteristic noise figure of transistors.

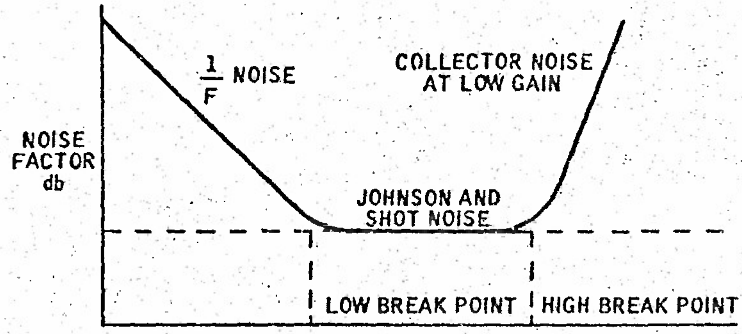


FIGURE 2-72
Transistor Noise

The low br ak point may be as low as a few hundred cycles in low noise circuitry. The high break point is a function of the alpha cut-off frequency of the transistor.

Another source of low level amplifier noise is mechanical chopper noise and chopper intermodulation. Choppers located at the input of an amplifier and any noise generated will be amplified by the amplifier. The following three items are sources of chopper noise.

a. Electrostatic noise is the result of capacitive coupling between the coil drive terminals and the contact terminals.

b. Magnetic noise is due to stray magnetic flux in the drive coil (or other flux sources such as transformers, solenoids, etc.) which are magnetically coupled into the signal leads.

c. Thermal noise and drift is the product of bi-metal junctions as seen in a thermocouple. The chopper drive coil will produce a certain amount of heat which, unless dissipated, generates temperature gradients across signal leads and thus generates unbalanced thermocouple junctions.

Chopper intermodulation is the result of the chopper frequency beating with AC input signals which are harmonically related to the chopper frequency. This is observed in some chopper stabilized amplifiers. In addition, poor filtering in a chopper stabilized amplifier may result in the chopper frequency or related harmonics feeding through to the output of the amplifier.

Noise magnitude will vary with the amplifier bandwidth and where necessary it should be verified that any noise figures are the worst case and not a "typical" value for a given bandwidth. Noise specified may be referred to either the input or output. When using high gain amplifiers the noise referred to the input (RTI) will probably be the worst case as the magnitude of the noise is the RTI noise figure multiplied by the amplifier gain.

A straightforward method of measuring noise is to load the input with a typical source resistance which is completely shielded and read the noise at the output terminals, either with an energy measuring RMS meter or a wideband oscilloscope. The measured noise will vary with gain and bandwidth, therefore the amplifier should be evaluated at all anticipated gain and bandwidth (where gain and/or bandwidth is variable) settings. The amplifier noise related to system noise will depend upon the type of load of the amplifier. An additional check is to perform the noise test with the actual load or with a filter having the same impedances (inductive, capacitive, and resistive) as the intended load.

2.2.9.3.2 Common-Mode Rejection in Amplifiers

The subject of CMR has been extensively covered in Section 2.2.6 and in the descriptions of the more common instrumentation amplifiers. Additional common-mode information is found in the Appendix. Amplifier specifications with respect to common-mode voltages will be discussed below.

a. CMR in Single-Ended Amplifiers. - Where this is specified, the limiting factors should be fully stated as the conditions will limit system flexibility.

b. CMR as a Function of Gain. - At low gains the amplifier may not meet the desired system requirements.

c. CMR in Low Pass Filter Amplifiers. - The bandwidth of an amplifier will affect the AC CMR capability and thus CMR should be given at all frequencies up to the highest signal bandwidth. The ability of the amplifier to filter out common-mode voltages such as 60 CPS will effectively raise the CMR capability - a feature which should be considered if a specific AC frequency is causing trouble and a narrow amplifier bandwidth is acceptable.

d. AC CMR Specifications. - Amplifier CMR is usually specified at DC and 60 CPS. Where other common-mode frequencies, such as 400 CPS are anticipated, the CMR should be found for the specific frequency. Some amplifier CMR values will remain essentially flat to more than 1000 CPS while CMR in other amplifiers will drop off at a rate of 20 db per octave or more.

e. CMR Voltage Limitations. - Many amplifiers are limited to common-mode voltage from 7-1/2 to 20 V DC or peak-to-peak AC. This may limit the use of some signal conditioning equipment, such as grounded and common strain gage power supplies, as well as require lower system common-mode voltages. voltages.

f. CMR at a Specified Line Unbalance. - Most amplifiers are rated at from 350 ohms to 1000 ohms source impedance or source unbalance to demonstrate CMR with a specified source unbalance.

2.2.10 ANALOG SIGNAL CONDITIONING

The transducers employed to measure physical parameters, such as temperature, pressure, vibration, and flow, do not ordinarily produce electrical signals exactly suitable to the requirements of the next stage of the data processing system. Consequently, signal conditioning equipment is used to amplify, attenuate, isolate, match impedance, or whatever is necessary to "condition" the transducer output signal for the processing system.

Some of the techniques recommended to condition analog signals prior to analog-to-digital conversion and recording are outlined in the following paragraphs.

2.2.10.1 Temperature

Two methods are commonly employed to measure temperature. One method uses thermocouples and the other uses a resistance-temperature probe or resistance-temperature bridge.

Since thermocouples must be referenced to a controlled temperature, such as 150°F, a reference junction is necessary. This junction may be located in a multiple-junction reference oven.

Reference junctions are constructed so that each circuit and its shield is carried separately through the junction. Each channel signal and its shield is carried separately through the system and terminates as shown at the isolating amplifier. The output shield and circuit is connected to ground at the readout instrument only.

Calibration of thermocouple channels is accomplished by means of a voltage from a precision voltage divider which operates from a precision regulated voltage source.

The second method of temperature measurement uses a four-arm bridge-type resistance-temperature transducer. The circuitry for this type of transducer is discussed in the next section.

2.2.10.2 Wheatstone-Bridge Type Transducers

Transducers for measuring such parameters as strain, load, pressure, and temperature, may all fall into the general classification of Wheatstone-Bridge or four-arm bridge transducers. Typical four-arm bridge circuits are shown in Figures 2-74 and 2-75.

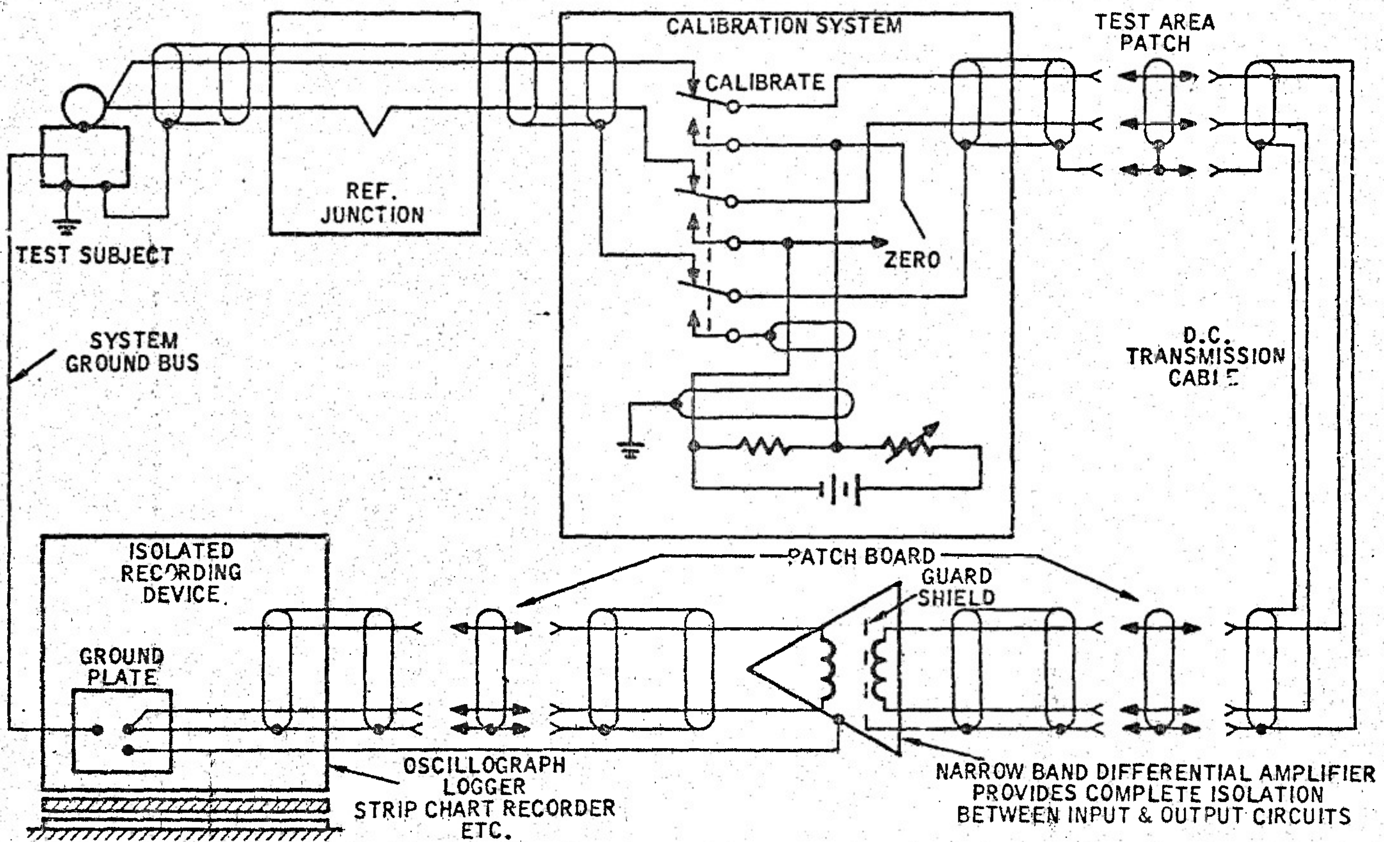


FIGURE 2-73
Thermocouple System

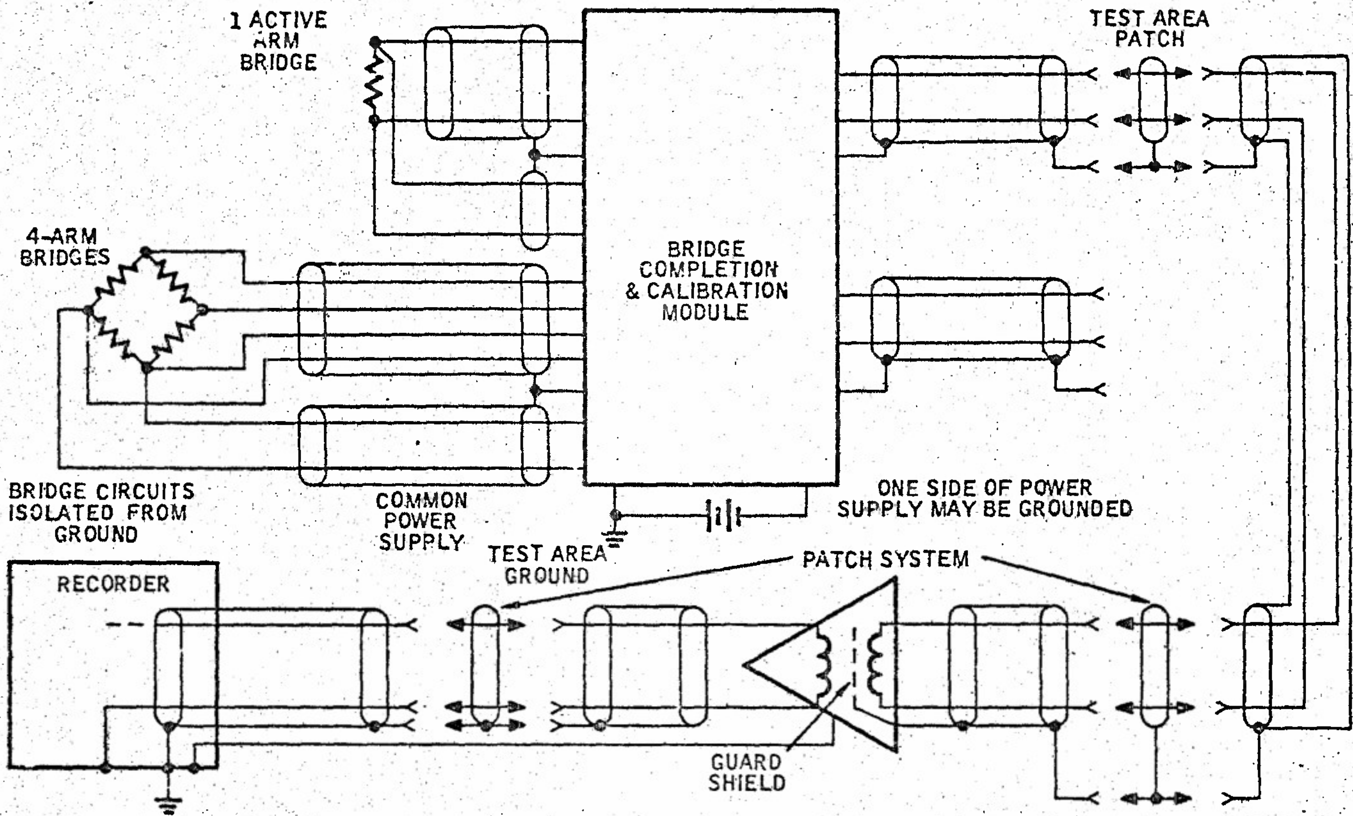


FIGURE 2-74
Bridge System
Common Power Supply, Narrow Band Differential
Amplifier Provides Input-Output Isolation

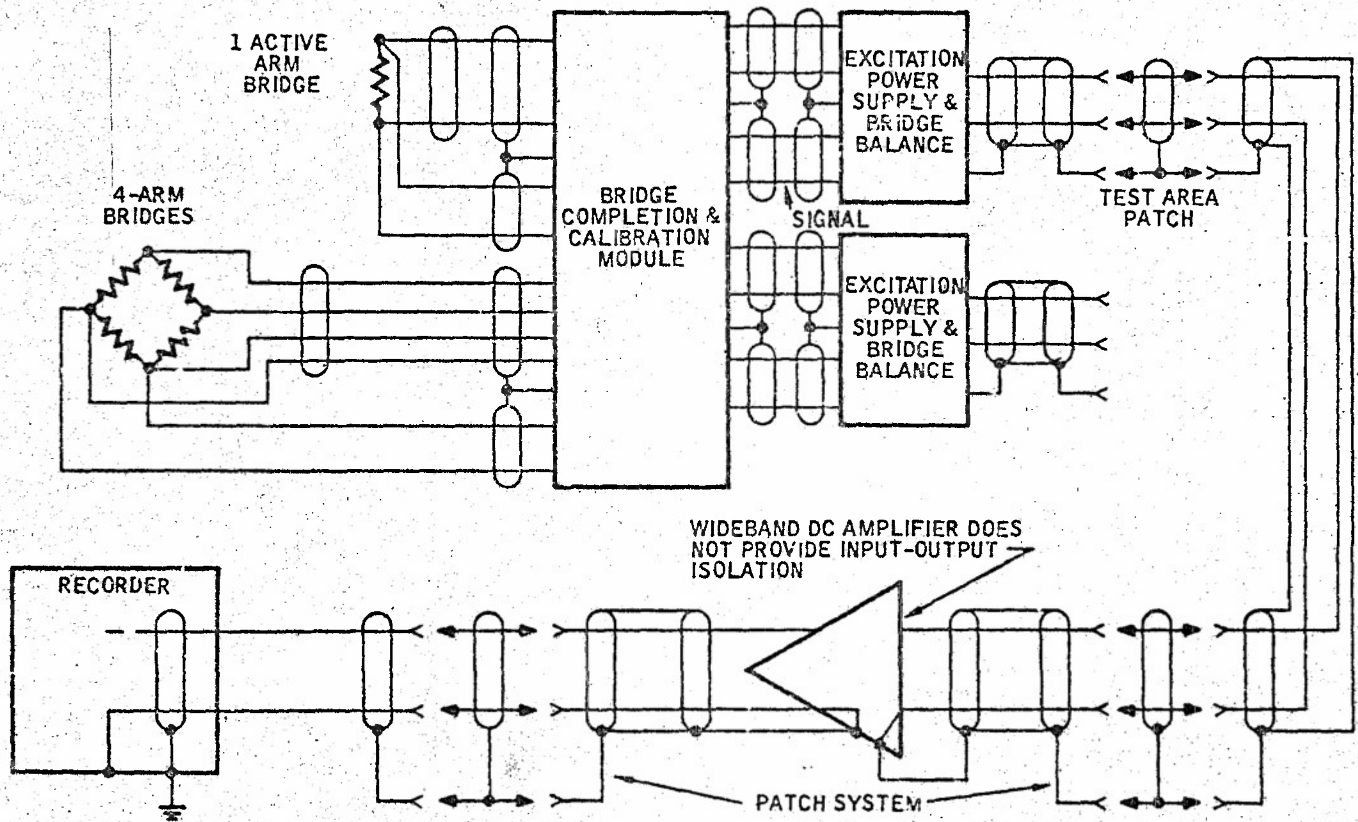


FIGURE 2-75
Bridge System
Individual Power Supply For Each Channel

Where a common excitation power supply is used, it is necessary to isolate the output of each bridge from any other by use of an isolation amplifier. This type of amplifier manifests high common-mode rejection and rather narrow bandpass characteristics. However, the input circuit is completely isolated from the output circuit of the amplifier. If a single-ended amplifier is used instead of a differential amplifier, one resistor in all of the bridges involved would be in parallel, as indicated by the dotted line on Figure 2-76.

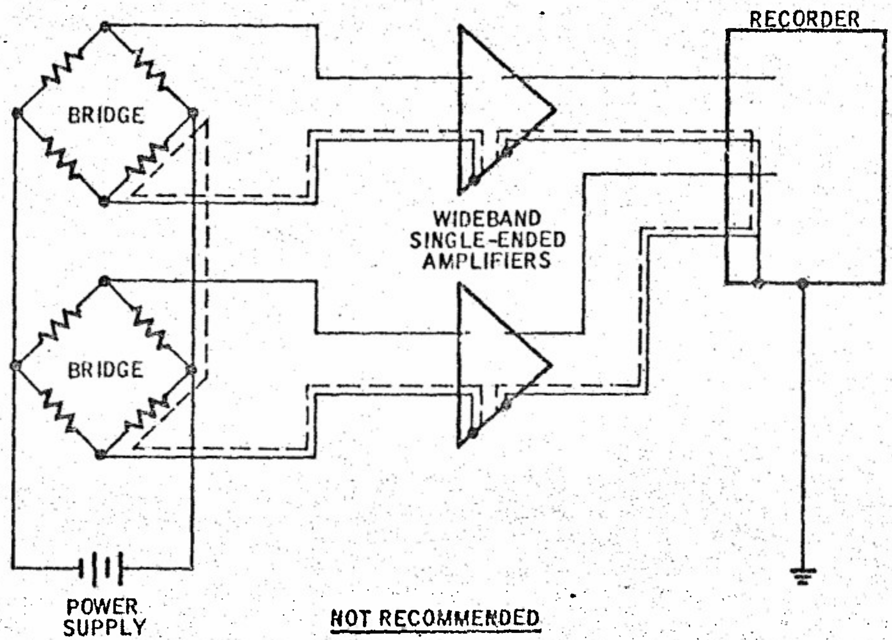


FIGURE 2-76
4-Arm Bridge Circuit Showing Short Circuit Caused By Use Of Non-Isolating Amplifiers

Where high-frequency response is required, such as may be obtained with strain and pressure transducers, the problem of isolating each bridge can be solved by using individual excitation power supplies. The circuitry of this type of supply is completely isolated from ground as is the bridge itself; therefore, a single-ended amplifier with wide bandpass characteristics may be used without introducing any grounding or cross-connecting problems.

Calibration of bridge circuits may be accomplished by the R-Cal or shunt calibration method or, if desired, by use of a known, selectable, substituted calibration voltage. The R-Cal method is shown in Figure 2-77. The calibration

voltage method is similar to that described for the thermocouple system. Both methods are equally accurate. The choice of which to use depends upon any secondary requirements of the circuitry. Where one- or two-arm bridge transducers are used, bridge-completion resistors can be mounted on printed circuit cards in the bridge-completion module.

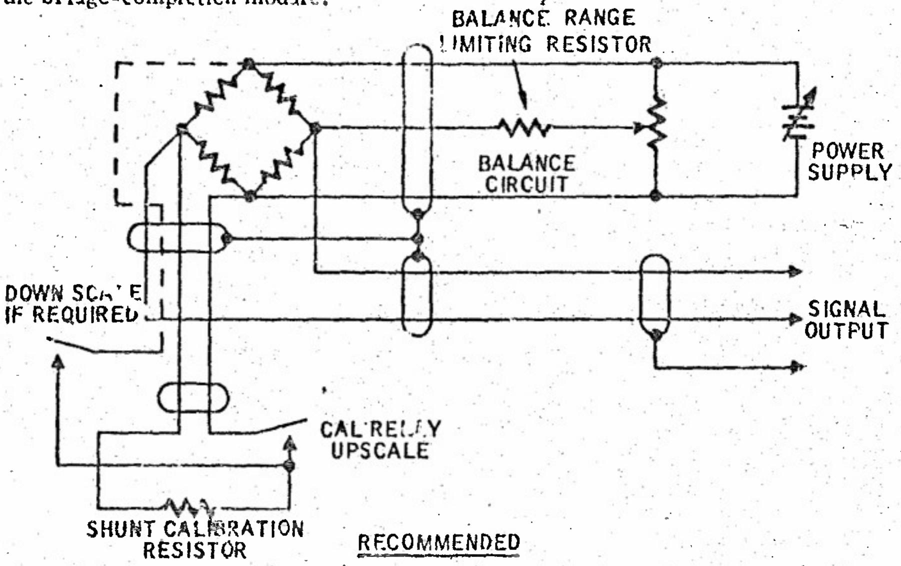


FIGURE 2-77

Typical Four-Arm Bridge Circuit Showing Balance and Calibration Methods

2.2.10.3 Vibration, Shock, and Acoustical Measurements

In general, vibration and shock may be measured by accelerometers or velocity pickups. Accelerometers are usually piezoelectric-type transducers. For low frequencies, strain gage accelerometers may be used. Accelerometers, mounted on a shock table, may be used to measure shock. Figure 2-78 shows a typical accelerometer circuit.

Acoustical pickups fall under the same general classification as accelerometers. A high sound-intensity microphone, such as the Altec 21BR condenser microphone, may be used.

The output impedance of accelerometers is normally quite high, requiring that a line-driving amplifier be mounted near the transducer. An amplifier is usually required that will drive long, low-capacity transmission lines at no appreciable loss with a frequency response of 0.4 CPS to 100 KC. All accelerometers and amplifiers should be isolated from ground to prevent ground-loop noise.

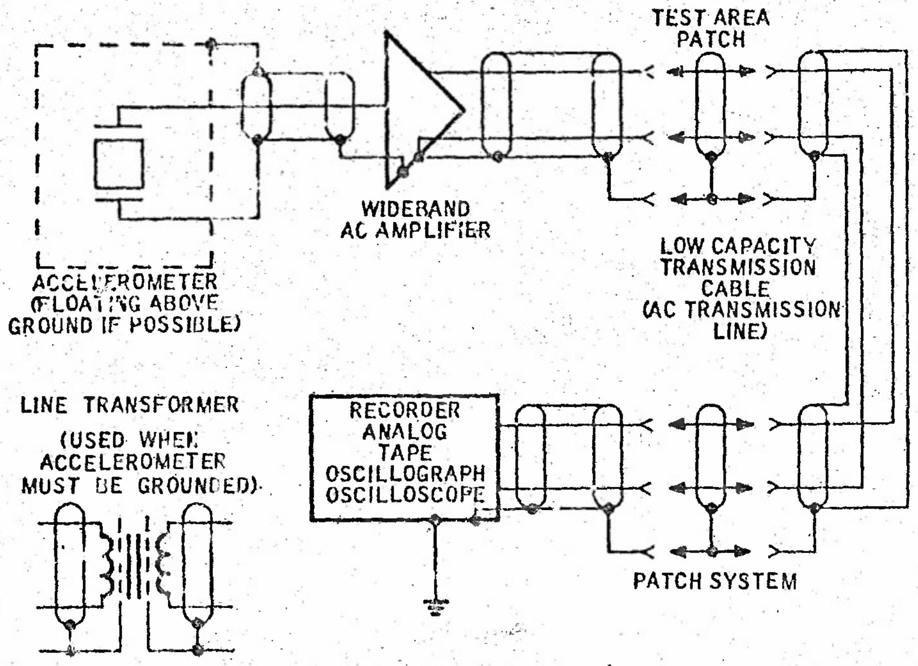


FIGURE 2-78
Acoustical Pickup or Accelerometer System

Acceleration signals may be recorded on analog magnetic tape or monitored on an oscilloscope. A Hughes Memoscope is very useful in recording shock tests. The Memoscope will trace one sweep on a CRT screen and hold the trace until manually erased. The scope trace could be photographed for future reference.

A high-speed recording oscillograph may also be used to record acceleration signals.

2.2.10.4 Flow and RPM Measurements

Liquid flow through pipes and rotational speeds are most commonly measured in terms of number of pulses per unit time.

There are several types of turbine-type flow meters and RPM transducers which produce a train of pulses such that, for each revolution, a certain number of pulses will be formed. Each transducer has a known conversion factor so that for any measured frequency output from the transducer the flow rate or RPM can be determined.

These pulses may be converted into useful informa.'on by a number of methods. One of these is an integrator. The pulse train is converted into a proportional DC voltage. This voltage can then be measured directly or converted to an equivalent digital value from which the equivalent flow rate or RPM can be determined.

A second method counts the pulses in a digital counter and samples the count at known time intervals. The integration function is then carried out by a computer.

Figure 2-79 shows a general flow or RPM system.

To eliminate problems in transmission of flow meter signals over long lines, a pulse shaper with isolation circuitry is recommended.

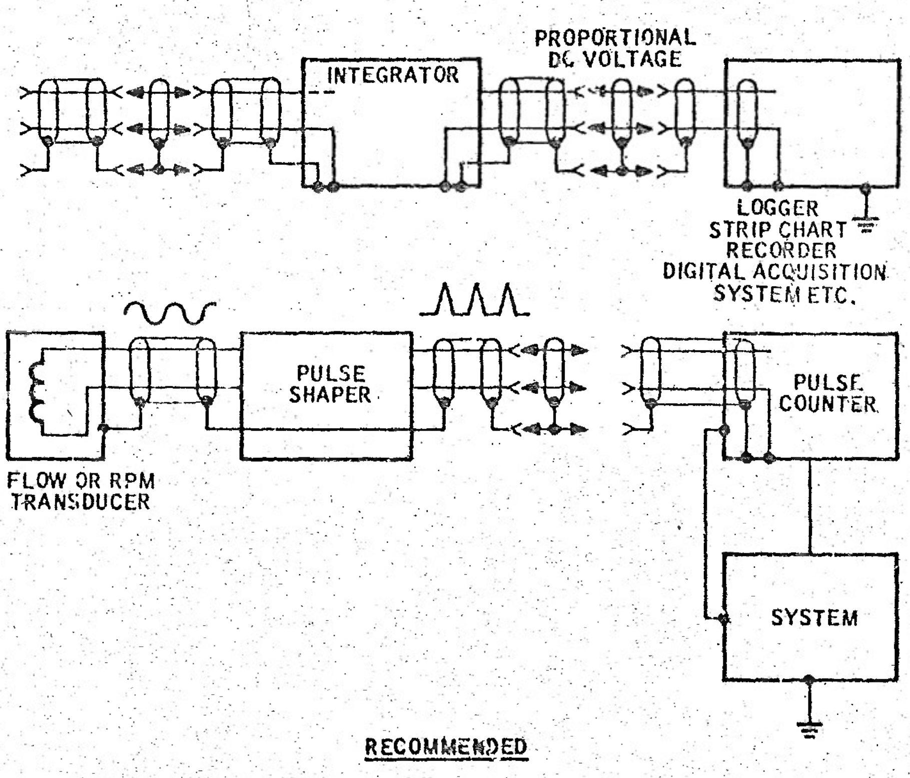


FIGURE 2-79
Flow or RPM System

3. RECOMMENDED SYSTEM DESIGN PRACTICES

The overall system design philosophy which is recommended for a low noise, high accuracy instrumentation data acquisition system may be outlined as follows (see Figure 2-33):

a. Provide power isolation transformers to data system equipment.

b. Isolate data system equipment cabinets from earth.

c. Provide a single-earth ground point at the test stand area for all instrumentation systems.

d. Ground data input instrumentation cable shields at test area ground.

e. The data system must have an isolated common ground bus or copper plate inside data system.

f. Provide maximum separation between instrumentation system and AC power equipment, such as generators, pump motors, etc.

A more specific coverage of the above outline is included in this section.

3.1 TEST SITE SELECTION

Good grounding and noise reduction should be among those considerations which are made in the selection of a rocket engine or component test site. Once a locality which is remote from dense population has been selected as the site area, the primary factors which govern the facility plan will most likely be personnel safety, convenient placement of test stands with respect to data recording area, and use of terrain as a construction aide (as in the case of vertical static firing structures).

Good grounding practices are sufficiently flexible to be adapted to practically any test site selected. The considerations which must be made to insure sound grounding in a new test site are described below:

3.1.1 PRIMARY POWER

The location of primary power lines form a major role in data accuracy and must be installed as follows:

a. Primary power lines must be located a minimum of 1/2 mile from the nearest test equipment.

b. All data transmission line runs must be oriented perpendicularly to the main power line run.

c. Feeder power to the facility may be run perpendicular to the main power lines and tapoff isolation transformers are recommended.

3.1.2 EARTH GROUND

Soil conductivity varies from one geographical area to another. The significance of soil conductivity is more in its relation to facility power than to an instrumentation system itself. If good soil conductivity exists along the path of primary power lines adjacent to a test facility, then ground currents originating from the power lines will be confined to an area close to the line path. Poor soil conductivity causes a wider spread of power ground current and is therefore more apt to cause interference with adjacent test facility circuits. It is recommended that underground copper or iron be used along primary power lines to trap ground currents, thereby reducing their effects on instrumentation data gathering. The single earth ground point is the proper procedure for instrumentation grounding.

For personnel safety, poor earth conductivity may be cause for installation of a counterpoise system. The counterpoise is a grid work or mesh usually of metal underlying the entire facility area. It is intended to "short" any earth currents and insure a reasonably low difference of potential between all earth grounding points in the facility. The "equipotential" capabilities of counterpoises are not sufficient to be taken advantage of in instrumentation system grounding. The instrumentation system must have its own independent grounding.

3.2 POWER

The power system design for a test facility can be accomplished in many different ways within the framework of electrical codes and modern design practices. Some of these practices may contribute to data acquisition system noise, some may attenuate noise, and some may have no effect. The following recommended practices were chosen because they either attenuate or do not actively contribute to the noise sources which are inherent in the power system. Eliminating all power system noise from the data acquisition system can probably be accomplished only by eliminating all power equipment and wiring from the area, an impractical

solution at the present time. Careful design of the power system will result in minimum noise contribution to the data acquisition system.

3.2.1 CODES

The electrical power system must be designed and installed in accordance with the National Electrical Code unless a local code takes precedence. The electrical codes specify minimum requirements which must be met in order to safeguard personnel and property. Most electrical codes have been based on experience with general industrial, commercial, and residential installations and there may be cases where a literal interpretation of the code would have a detrimental affect on the data acquisition system.

Any deviations from the code should be carefully considered from the standpoint of personnel safety before a variance is requested from the authority enforcing the code. There must be no compromise with safety in the design of the electrical power system.

3.2.2 EARTH GROUND CONNECTION

The power system earth connection as required by the Code will have little affect on data acquisition system noise. The Code requires that:

a. A metallic underground water piping system always be used as a grounding electrode where available.

b. The connection to earth present a maximum resistance to earth of 25 ohms.

c. Where a suitable piping system is not available or has a resistance of greater than 25 ohms, additional electrodes, such as ground rods, must be installed.

Because of the size of electrical service and accessibility of utilization equipment in the typical test facility, it is recommended that other electrodes be installed in addition to the underground water piping system. An earth connection of less than 5 ohms resistance under the dryest soil conditions should be the design goal.

The earth connection should be designed so that future inspection, resistance checks, and expansion can be made. The following procedures should be considered for earth connections:

a. Connections between cables and ground electrodes should be accessible for inspection by installing a tile or meter box with removable cover, flush with grade level, around the top 12 to 18 inches of the ground rod.

b. Connections to ground electrodes should be bolted rather than welded to facilitate future ground resistance checks.

A typical installation is shown in Figure 3-1. The actual design of the earth connection scheme, including initial calculation of ground resistance, type and placement of ground electrodes, chemical treatment of the soil where indicated and ground resistance measurements of the completed system is well documented in available literature (see the Bibliography).

3.2.3 POWER SYSTEM GROUND

Whether or not the power system must be grounded at various voltage levels is well defined in the Code. Within a test facility, the only common voltage level which may not require a connection to ground is 480 V. If lighting fixtures are supplied directly from the 480 V system, then the system neutral must be grounded. Otherwise the 480 V system may be grounded or isolated from ground at the option of the design engineer.

The choice should be considered based upon the effect on data acquisition system noise. Of primary importance is a separate ground system for power and instrumentation and the possibility of large unbalanced power currents being returned to earth. The advantages and disadvantages of grounding are thoroughly discussed in available literature. [7, 49]

3.2.4 EQUIPMENT GROUNDING

The Code requires that all exposed non-current carrying metallic parts of equipment and conductor enclosures be provided with a low resistance path to ground. The separate pieces which make up a complete conductor enclosure (such as lengths of metallic conduit) and separate metallic equipment enclosures must be bonded, either by adequate metal-to-metal contact between the pieces themselves, or by separate bonding jumpers where required, to form the low resistance path. Other means, such as connecting an equipment enclosure to grounded structural metal, are acceptable.

Surrounding all runs of power conductors with a grounded metallic enclosure offers the additional advantage of electrostatic shielding in a test facility. Careful bonding and grounding of conductor enclosures will provide electrostatic shielding of the power conductors from data acquisition system signal conductors.

3.2.5 WIRING, CONDUCTOR ENCLOSURES

Enclosures around insulated power conductors are required in most environments by the Code to furnish mechanical protection for the conductors. Conductor enclosures can be generally divided into two groups: metallic and nonmetallic.

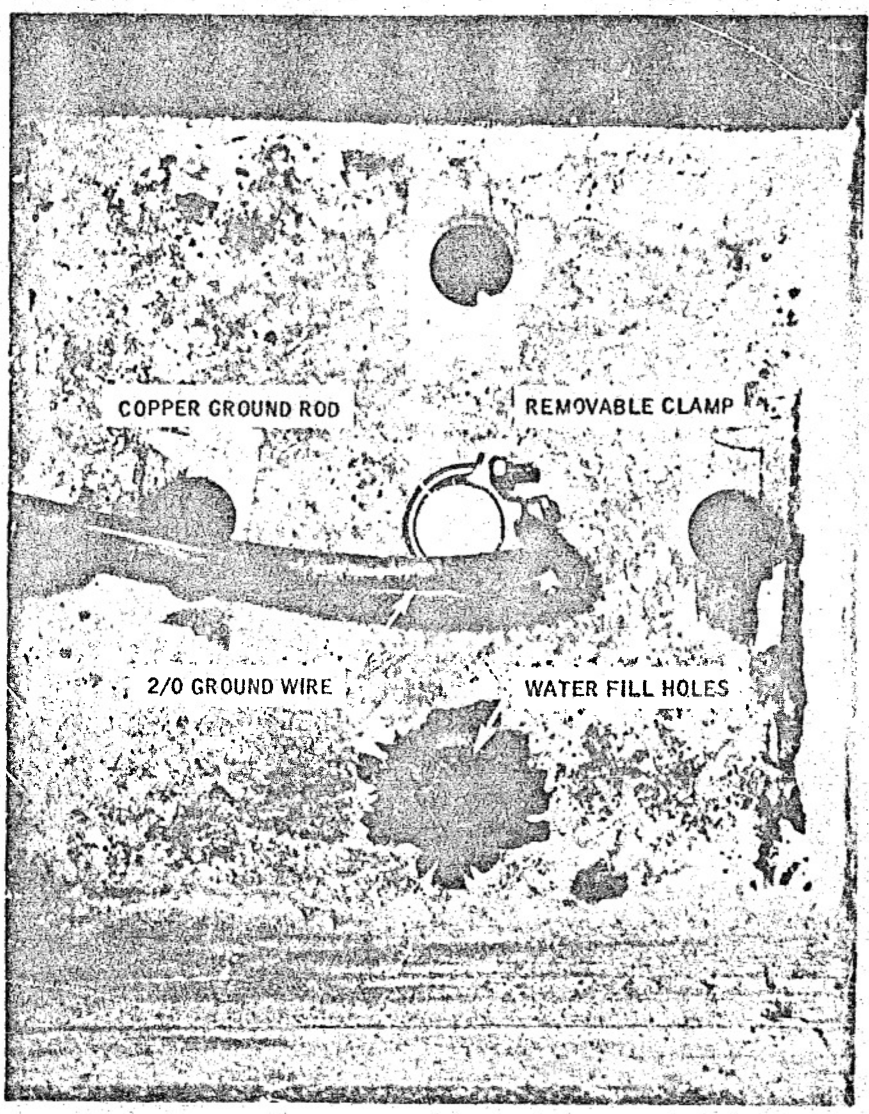


FIGURE 3-1
Ground Rod Installation To Permit Inspection, Testing, and Maintenance

The enclosure may be an integral part of the power conductor assembly, as in the case of three-conductor armored cable, or the enclosure may be separately installed with the conductors installed in a separate operation, as typified by conductors in conduit or wireway.

In a test facility, metallic conductor enclosures should be used for power conductors wherever possible for the shielding which they provide. Use non-metallic rigid conduit and non-metallic cable trays, to minimize capacitance of the conductors to ground and to provide equipment to earth ground isolation for the instrumentation system.

Some of the commonly used conductor enclosures which are suitable for use in a typical test facility are:

a. Conduit - Conduit may be metallic or non-metallic, rigid (heavy-wall) or electrical metallic tubing (thin-wall) and is available in such materials as steel, aluminum, copper, PVC plastic (polyvinyl-chloride), asbestos cement, fiber, soapstone, and vitrified clay. From the standpoint of noise attenuation, rigid steel conduit is the most effective enclosure for power conductor and this should be used wherever practical throughout the test facility. Use of electrical metallic tubing or rigid aluminum or copper conduit will provide as effective an electrostatic shield as rigid steel but the electromagnetic shielding properties of the steel conduit are at least an order-of-magnitude better than those of aluminum or copper.

b. Flexible Conduit - The Code allows the general use of flexible metallic conduit as a conductor enclosure in some applications. Because of its construction, flexible conduit is a poorer electrostatic shield than any of the solid metallic conduits and provides considerably less electromagnetic shielding than rigid steel conduit. It is recommended that flexible conduit not be used as a general conductor enclosure in a test facility and that its use be restricted to short lengths where required to absorb vibration or to permit position adjustment of the device served.

c. Wireway - A wireway consists of a rectangular sheet metal duct-like enclosure with a hinged or removable cover. Expanded or whole sheet metal may be used. Wireways are sometimes used where a number of power circuits are to be carried through an area. They are especially useful where numerous taps are to

be made along the length of the run. A wireway is considerably less effective in the attenuation of radiated noise than rigid conduit. Its use is not recommended in close proximity to data acquisition system equipment and signal conductors.

d. Armored Cable - Armored Cable is an assembly of insulated power conductors (usually three) twisted together and covered with an over-all metallic jacket or armor. It is used in lieu of conduit and conductors in larger conductor sizes and is often installed in continuous rigid cable supports (cable tray). The armor may be steel, aluminum, or bronze. The armor acts as an electrostatic shield but is not as effective as rigid steel conduit in attenuating electromagnetic fields. Rigid steel conduit will provide considerably more attenuation of power system noise in areas occupied by data acquisition system equipment and signal conductors.

3.2.6 WIRING, CONDUCTORS

Power system insulated conductors for 600 V and less will generally be of two types except under unusual or severe environmental conditions. The two types differ only in insulating material, one being a thermoplastic, the other rubber. There is nothing to recommend one over the other from a noise standpoint. Above 600 V, there are two common insulation levels, 5000 V and 15,000 V and insulation is usually rubber or cross-linked polyethylene. At these voltage levels, the conductor is usually provided with an electrostatic shield in the form of a copper tape over the outside of the insulation. (At 5000 V the shield is optional.) The primary purpose of the shield is to assure uniform voltage stress throughout the insulation and, when properly grounded, to prevent the build-up of hazardous potentials at the insulation surface. The shield also effectively contains the electrostatic field and prevents the formation of corona. In a test facility, shielded cable should be specified at the 5000 and 15,000 V levels.

Where power conductors are to be run outdoors and it is impractical to install them underground for voltages up to 15,000 V, pre-assembled aerial cable should be used in preference to open wiring. Pre-assembled aerial cable consists of three insulated, twisted conductors fastened to a messenger cable by means of a copper binding strip. The electromagnetic field produced by this assembly is much less than that produced by open conductors.

Bus duct, which is an assembly of buses insulated from one-another and provided with a sheet metal enclosure, is sometimes more economical than insulated power cables in conduit where large currents must be handled. Although the sheet metal

enclosure provides an electrostatic shield, the bus conductors are relatively far apart and cannot readily be twisted, resulting in a relatively strong electromagnetic field. The installation of bus duct in rooms containing data acquisition system equipment and conductors should be avoided.

3.2.7 WIRING, INSTALLATION

There are two practices which should be followed in the installation of power conductors at a test facility:

a. Maintain the maximum practical separation between electrical power conductors and physically parallel data acquisition system conductors. As power conductor voltage and current and the length of run over which the conductors are parallel increase, the importance of separation increases.

b. Twist power conductors or use multi-conductor power cables for all circuits in the vicinity of data acquisition equipment and signal conductors. It is recommended that all power conductors in the test facility carrying more than 5 AMP be twisted. However it is also a good practice to twist all AC power lines regardless of the current. A suggested rate of twist is one complete twist for each length equal to approximately 25 times the diameter of the insulated power conductor.

3.2.8 POWER TRANSFORMERS

All electrical power system three phase transformers used in the test facility, including the main electrical service transformer(s) should have at least one of their windings connected in delta to provide a path for triplens. Failure to provide a delta winding will result in relatively large values of triplen voltages or currents in power conductors and the effects of electrostatic and electromagnetic coupling increase with frequency.

3.2.9 ROTATING EQUIPMENT

Rotating equipment can be a source of radio frequency noise. This can be minimized by the following practices:

a. Use squirrel cage induction motors which utilize slip rings or commutators wherever possible.

b. Where necessary to specify motors with commutators, specify units properly designed electrically to minimize arcing at the commutator. For example, inclusion of interpoles in a DC machine increases commutation efficiency and reduces arcing.

c. Arcing at the commutator or slip rings can be decreased by careful mechanical design such as adequately sized shaft and bearings to maintain concentricity between commutator or slip rings and bearing to minimize brush bounce and vibration.

3.2.10 POWER EQUIPMENT LOCATION

Electrical power equipment such as transformers, line voltage regulators, motors, generators, and switching devices should be separated no less than 250 feet from data acquisition system equipment and conductors. Much of the electrical power distribution and control equipment is frequently placed in a separate equipment room and the architectural arrangement of the test facility should allow this minimum distance between this room and the data acquisition system. This also applies to heating, ventilating, and air conditioning equipment which utilizes electric motors and control switching devices. The maximum distance will be limited by the voltage drop which can be tolerated in feeders to the data acquisition system equipment. This must be considered in initial planning and may result in a compromise.

3.2.11 LIGHTING

Electric discharge fixtures are sources of radio frequency noise. In some areas which do not require high intensity illumination, such as data transmission line tunnels or corridors and termination areas, incandescent lighting* should be used. In other areas such as the operating rooms of the data acquisition center, fluorescent fixtures must be used in order to obtain higher intensity and a better quality of illumination.

If the data acquisition system is sensitive to radio frequency noise, the noise can be reduced to a tolerable level by specifying radio frequency shielded and filtered fluorescent fixtures. Fluorescent fixtures are available which meet military specifications MIL-I-16910A, MIL-I-26600.

3.3 GROUNDING (ANALOG AND DIGITAL)

The methods of performing analog and digital grounding are given separate consideration in this handbook although the physical principles of noise reduction for both are basically the same.

3.3.1 ANALOG SIGNAL GROUNDING

The objectives in designing an instrumentation analog system ground are as follows:

a. To remove common-mode voltages as much as possible

b. To keep digital grounds separated from analog grounds.

If single-ended amplifiers are used between transducers and recording devices, it is recommended that either the transducer or the recording device be left

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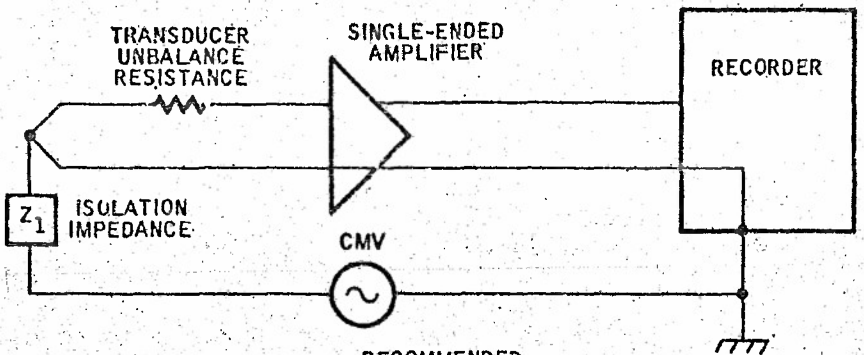
*Incandescent lamps can be sources of current transients due to sudden changes in filament resistance as lamps are turned on.

disconnected to both system and earth ground. Figure 3-2 illustrates the grounded recorder with an ungrounded transducer configuration. By isolating the transducer, only a small amount of CMV error current will flow through the low side of the signal line because of the high isolation impedance Z_1.

Similarly, in the other situation where the transducer is grounded, the recorder is isolated from ground through the high impedance Z_2, illustrated in Figure 3-3. Thus, CMV error will be minimized because the CMV error current must flow through Z_2 which should be several hundred megohms in magnitude.

The circuit of Figure 3-4, with both transducer and recorder grounded is not recommended becuase of the closed loop path ABCD with CMV applied through the amplifier low side signal line. Even if line A-B is a heavy ground bus, some CMV may exist due to magnetic noise coupling into the loop ABCD from adjacent power or high current AC equipment. The larger the loop area the more susceptible will be the circuit to magnetic noise coupling.



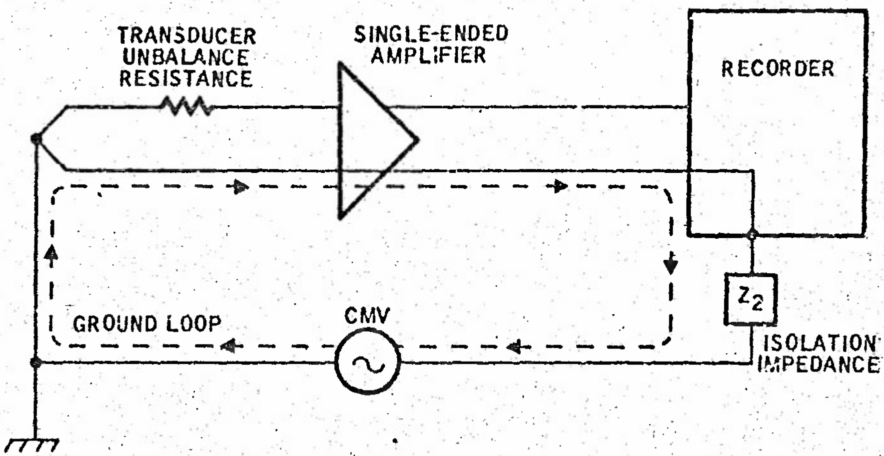
RECOMMENDED

FIGURE 3-2
Isolated Transducer-Grounded Recorder

Therefore, it is recommended when single-ended amplifiers are used, that either the transducer or recorder be left ungrounded.

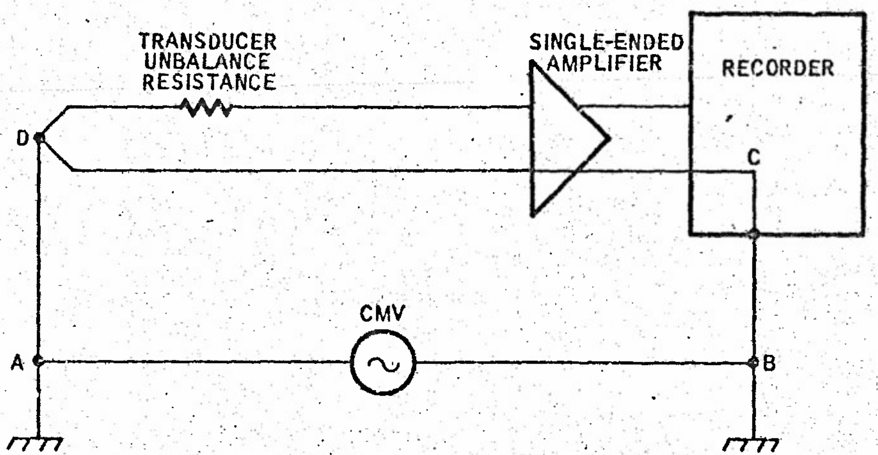
The ground bus, if properly used, is intended to reference the test transducer area and the recording to the same potential in order to provide a single path to earth ground for the system grounding. By earth grounding the ground bus at only one point, the earth common-mode potential is no longer part of the system. The only common-mode voltage then present in the system will be that which is capacitively or inductively coupled from outside circuits.

Separation of analog and digital grounds is mandatory since digital signals can cause extremely high noise content in analog measurements. Figure 3-5 illustrates a typical problem encountered when analog and digital grounds are not separated.



RECOMMENDED

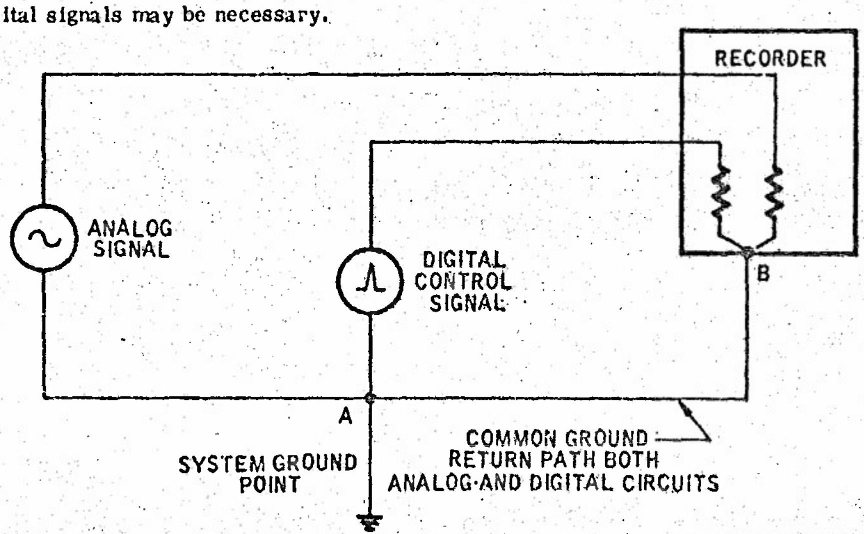
FIGURE 3-3
Isolated Recorder-Grounded Transducer



NOT RECOMMENDED

FIGURE 3-4
Grounded Transducer - Grounded Recorder

Separation of the analog and digital paths is necessary in order to avoid interference from digital circuits to analog signals along the path A-B. Isolation can be accomplished by the basic method shown in Figure 3-6. Note that the digital and analog circuits have no paths in common. It is also shown that isolation may not be this simple in all cases and that the use of isolation transformers for digital signals may be necessary.



NOT RECOMMENDED

FIGURE 3-5

Common Analog and Digital Ground Returns

3.3.2 DIGITAL GROUNDS

The excellence of a digital grounding system or ground "plane" becomes more recognizable as the frequency or speed of the digital logic increases.

Digital systems (now mostly solid state) can generate large quantities of pulse current due to quantities of circuits carrying simultaneous signals such as clock pulses. Magnetic flux changes d/dt are proportional and can cause adverse pickup effects on adjacent wires. The best method of avoiding magnetic interference is to insure that each signal wire and lead is as close as possible to the digital ground to avoid susceptible "area loops". A ground "plane" is recommended since it is available at all areas of the system and is therefore convenient for adjacent placement of most lead lengths. Such a ground plane is described in Section 2.2.1.2.3.

Pair twisting can also eliminate both coupling and receiving of magnetically radiated noise. This technique is effective, but may be costly and impractical if a

great quantity of digital cabling is involved because it means including one ground return for each digital signal wire.

Capacitively (electrostatically) coupled digital noise is not ordinarily the problem as is magnetically coupled noise. Electrostatic shielding (copper braid) is therefore not required in most digital applications. In fact, shielding may often be a detriment since it increases the digital signal-to-ground capacitance and may thereby load the signal source to a degree that rise times are too slow to perform their intended function.

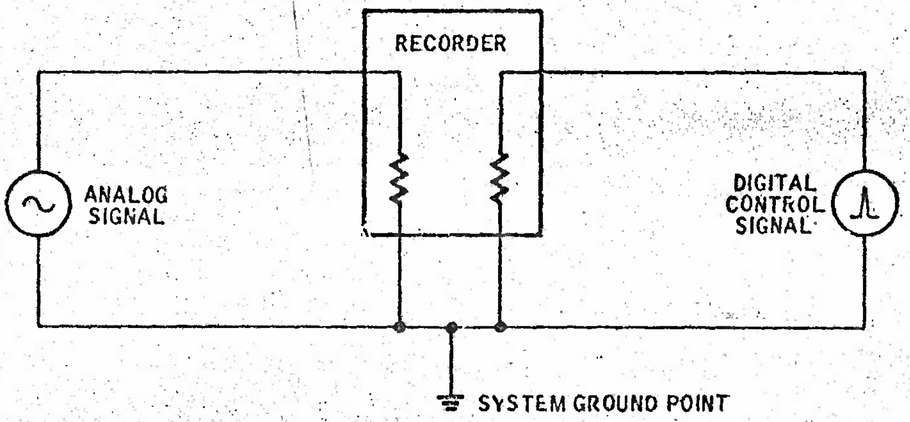


FIGURE 3-6

Isolation of Analog and Digital Ground Returns
Except at One Point

4. INSTRUMENTATION SYSTEM

In the previous section noise sources and noise reduction were considered in detail with relation to an overall data system. It is also important to consider each major subsystem and its noise susceptibility and noise contribution to the overall system such as; signal conditioning equipment, how the various signal conditioning equipment is used, and proper installation to reduce noise and ground loops. Amplifiers are considered on the basis of common amplifiers in use, types of amplifier (single-ended or differential), and errors and noise introduced into the instrumentation system by the amplifier. In addition, the instrumentation and Data Acquisition equipment (e.g. oscillographs, tape recorders, etc.) are considered in regard to the proper grounding of these systems to improve over-all system accuracy and eliminate system susceptibility to ground loops and noise. Other topics in this section include: transducer errors and grounding techniques; low frequency data transmission lines; isolation of equipment cabinet and power from the instrumentation, etc.; proper grounding and implementation of equipment cabinet grounding when one or several cabinets are a part of the data system; connection to the common ground plane in regards to loading; equipment grounding, and test area instrumentation grounding and ground bus techniques of data system connection to a single ground point at the test area.

4.1 TRANSDUCERS

The transducer is the link between the physical parameter (pressure, temperature, etc.) of interest and the desired electrical signal which corresponds to the physical parameter. The choice of the type of transducer for a given application will depend on many factors. These include: environment, parameter to be measured, accuracy, signal conditioning equipment and output signal desired, etc. Table 4-1 references many of the physical parameters, and the types of transducers which are used in instrumentation systems.

A further distinction in transducers can be made if the unit is of the self-generating or passive type. Figure 4-1 illustrates these two categories. This difference is more apparent in Figure 4-2 which shows two simplified transducer configurations for measuring temperature. Each type of system has its advantages and limitations, both in the types of transducer units available and in the type and complexity of the signal conditioning equipment.

Included in this section is a discussion of the transducer amplifier which is becoming more popular in all instrumentation systems as a source of high level low impedance data signals.

A brief description of common transducers in use today and will be discussed in terms of their output signal level and source impedance in the following paragraphs.

PHYSICAL PARAMETER	TRANSDUCER TYPE						
	SELF GENERATING				PASSIVE		
	MAGNETO ELECTRIC	PHOTOELECTRIC	PIEZOELECTRIC	THERMOELECTRIC	CAPACITIVE	INDUCTIVE	RESISTIVE
Acceleration	0		0		0	0	0
Displacement	0	0	0		0	0	0
Flow	0		0		0	0	0
Force			0			0	0
Moisture					0		0
Level		0	0		0		0
Light		0		0			0
Mass	0		0			0	
Pressure	0		0	0	0	0	0
Temperature		0		0			0
Thickness		0	0		0	0	
Velocity	0	0	0		0	0	0
Viscosity			0		0		0

TABLE 4-1
Transducer Application

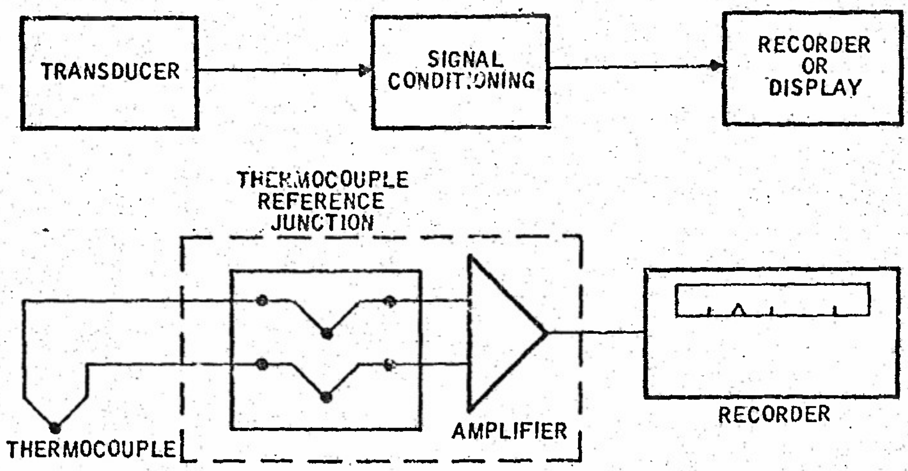


FIGURE 4-1
Self Generating Transducer System

4.1.1 TRANSDUCER SUMMARY

Electromagnetic self-generating transducers utilize the electrical energy generated when an electrical conductor cuts through a magnetic field. Examples of this type of transducer are the tachometer generator, the rotating magnet flowmeter pulse generator, and the coil and magnet linear velocity vibration pickup. Source impedances will range from a few hundred ohms to a few thousand ohms and output signal levels vary from millivolts to volts full-scale.

Photoelectric transducers, such as the phototube and the photo voltic cell, are used to measure light spectrum and/or intensity. Though considered self-generating, these units are commonly used with special electronic amplifiers and the output characteristics would be that of the related amplifier to the system application. Photosensitive transducers or sensors are considered in the passive resistance section.

Piezoelectric transducers are widely used for high frequency vibration and transient measurements. The piezoelectric crystal possesses a high source impedance and high output. Because of the source, high impedance special signal conditioning equipment such as the charge amplifier or special emitter (cathode) follower amplifiers are required and the output impedance and signal level will reflect the type of amplifier involved. The signal frequency will range from near DC to frequencies in excess of 5000 CPS.

Thermoelectric transducers consist primarily of thermocouple devices and are one of the most widely used sensing units. Signal outputs range from 20 to 75 MV full scale depending on the type of thermocouple. The source impedance will

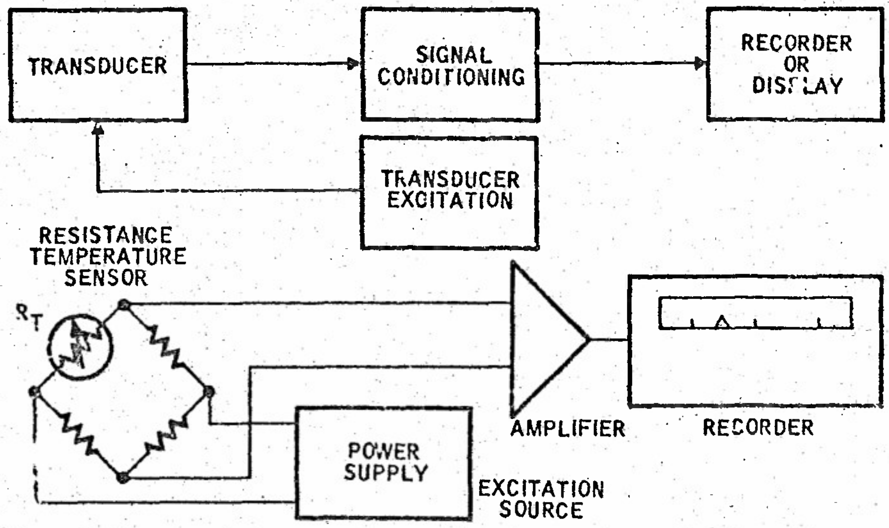


FIGURE 4-2
Passive Transducer System

nominally be less than 100 ohms unless quite long runs of high resistance thermocouple lead wires are used.

Capacitive transducers are usually used in conjunction with special RF or AC carrier systems. The output signal may take the form of an FM signal or DC voltage, depending upon the type of signal conditioning used. The source impedance and signal level will be that of the required signal conditioning equipment.

Inductive transducers, like capacitive transducers, require special signal conditioning equipment and signal characteristics will be that of the related output device.

Resistive transducers are among the most versatile and consist of many varieties of resistive sensors. These include strain gage, potentiometer, temperature sensitive resistors, thermistors, photo resistive cells, etc. These units are often used in a wheatstone bridge configuration or as a direct signal source such as the potentiometer or temperature sensitive resistor when provided with an excitation source. As the type of transducers are many, the output level and source impedance of resistive transducers is quite varied. Strain gages most commonly have source impedances of 120 and 350 ohms and outputs of 20 to 40 MV full scale depending on the amplitude of the excitation voltage or current. Semi-conductor strain gages will produce up to 250 MV or more with the same level of excitation as the 20 to 40 MV full scale conventional gage.

Potentiometer transducers nominally have source impedances from 1000 to 10,000 ohms and an output full scale signal of 10 or more volts depending on the excitation source. Other resistance type transducer signal levels and source impedances may range anywhere between the values for strain gage and potentiometer transducers. Resistive transducers may use common or isolated power supplies and may or may not be grounded. A wide range of signal conditioning equipment is available for this type of sensor.

4.1.2 TRANSDUCER ERRORS

Electrical errors such as those created by common-mode voltages, noise, and other electrical interference, have been extensively discussed in Section 2. There is an additional source of error in measurements related to the transducer which is involved when overall system accuracy is considered. These are equipment, installation, and dynamic response errors.

Equipment errors are related directly to the transducer and associated signal conditioning equipment, and are a function of linearity, hysteresis, stability, calibration, and environment. Transducer data sheets published by the manufacturer will provide information on some of the above characteristics.

Equipment errors can be summarized as follows:

a. Linearity and hysteresis are functions of the physical characteristics of transducers. A complete transducer calibration and calibration curves will allow for data correction techniques such as scaling, linearizing, offset correction, etc. by the data system

b. Instability such as zero and range drift add significant error to transducer output. Specification of stability should be carefully considered in relation to system reliability and accuracy

c. Environmental susceptibility will cause considerable error in transducers. Whenever a transducer is to be used for a critical measurement, an evaluation of the transducer must include tests at the expected environment and a complete calibration and characteristic curve be obtained.

Installation errors of transducers reflect the variation between the actual physical parameters under test and what the transducer actually measures. Installation errors can be minimized by:

a. Selection of correct location for each transducer. Typical examples include location of vibration sensitive transducer on a test item being subjected to a vibration test. The test item may have nodes of minimum vibration at which the transducer may be placed

b. Maintaining close liaison between test engineer and instrumentation engineer in order to obtain maximum usefulness of each transducer.

Transducer loading errors are changes introduced into a system by the transducer interfering with the normal operation or characteristics of the system. Typical transducer loading errors are:

a. Flowmeters or temperature probes located in transfer lines

b. Large mass transducers in vibration tests

c. Heat conductive thermocouple leads in high accuracy temperature measurements.

A reduction of transducer loading errors can be realized by one or a combination of the following items:

a. Locate all flowmeters and temperature probes in continuous lines and points where turbulence or mixing of fluids, gases, etc. are not present

b. Use minimum mass transducers on test items in a vibration test

c. Provide minimum dissipation transducer elements in high accuracy temperature measurements.

Dynamic response errors are the results of the limited frequency response of a given transducer with respect to the physical parameter under test. Typical response errors are:

a. AC coupled transducers will not respond to a static offset and would not be used in applications which measure slowly ranging functions

b. Thermocouples welded to a test specimen will have a much faster response time (thermal time constant) than thermocouples encapsulated in a test probe

c. All transducers contain some characteristic (thermal, electrical or mechanical) which will limit the instrument's frequency response and show up as phase, amplitude, or waveshape distortion of the output signal.

To obtain data concerning dynamic performance of a particular transducer the dynamic performance of the instrument should be tested. The test method may consist of:

a. Simulating the specific physical parameter to be measured

b. Application of a st - function will provide information related to the transducer response to rapid parameter changes.

4.1.3 TRANSDUCER CALIBRATION

4.1.3.1 Direct Calibration

Direct calibration involves subjecting the transducer to the actual physical parameter under test such as temperature or pressure. This method:

a. Is only as accurate as the calibration source

b. Requires elaborate calibration equipment

c. Difficult to perform with many types of dynamic transducers

d. Provides overall system check.

Inaccessible transducers or parameters which are difficult to duplicate limit the possibility of direct calibration.

4.1.3.2 Simulated Calibration

The simulated calibration of transducers depend to a large extent on calibration curves or known parameters such as tabulated thermocouple voltage output. Simulated calibration includes:

a. Voltage substitution for thermocouples

b. Resistance substitution for resistance type transducers

c. Shunt calibration of strain gage bridges, etc.

In this type of calibration the transducer is a part of the test circuit and an overall "end-to-end" data system check is possible. The biggest advantage to the simulated calibration is that it may be automated and completed in a matter of minutes prior to operation while a direct calibration may involve many hours.

Transducer calibration should reflect the expected operating range of the units. Typical operating ranges are from 60 to 85% of the full scale transducer range. The range of the transducer should be selected relative to the magnitude of the physical parameter involved.

A change in the type of transducer or method of obtaining the desired measurement will often improve the accuracy of the desired data such as:

a. Small temperature changes are best measured with a thermistor type unit

b. Large temperature variation measurements are improved by using a resistance temperature unit or thermocouple

c. Differential transducers are used where small gradient changes are to be measured.

4.1.4 TRANSDUCER SHIELDING AND GROUNDING

The shielding and grounding techniques used for transducers may have significant effect upon the noise it introduces into the data measurement. The following methods are recommended to eliminate or greatly reduce this noise.

a. Grounded Transducers

1. Insure solid earth ground connection

2. Provide a single common ground reference point for all grounded transducer in each test area. See Figure 4-3.

3. Connect instrumentation cable shield of each data channel as close to transducer ground connection as possible

4. Use twisted shielded thermocouple extension wires

5. Use a floating load on output of single-ended data amplifiers when amplifier input is a grounded transducer

6. Connect guard shield of data amplifier to input cable shield

7. Always use insulated shielded cables. Uninsulated shields should never be used in data instrumentation systems.

b. Ungrounded Transducers

1. Provide a single common ground reference point for all cable shields

2. Ground all input cable shields at test stand ground point

3. Provide a continuous shield "blanket" from transducer case to the input of the data amplifier

4. Connect data amplifier guard shield to input cable shield

5. Do not allow more than one ground connection in each input cable shield.

6. Use twisted shielded cables for all instrumentation cables, including floating thermocouple type transducers

7. Always use insulated shielded cables.

4.2 AMPLIFIERS

Improper grounding of data amplifiers can be a source of noise by creating ground loops and amplifying common-mode to normal-mode conversion noise. The following procedures should be adhered to when using and grounding data amplifiers:

a. Grounding Design Rules for Using Single-ended Amplifiers

1. Individual isolated excitation power supplies should be used with all bridge type transducers

2. Only one earth ground point must be used for recorder system; ground point should be same ground point as transducer ground

3. Provide chassis ground connection to data system ground bus (plate)

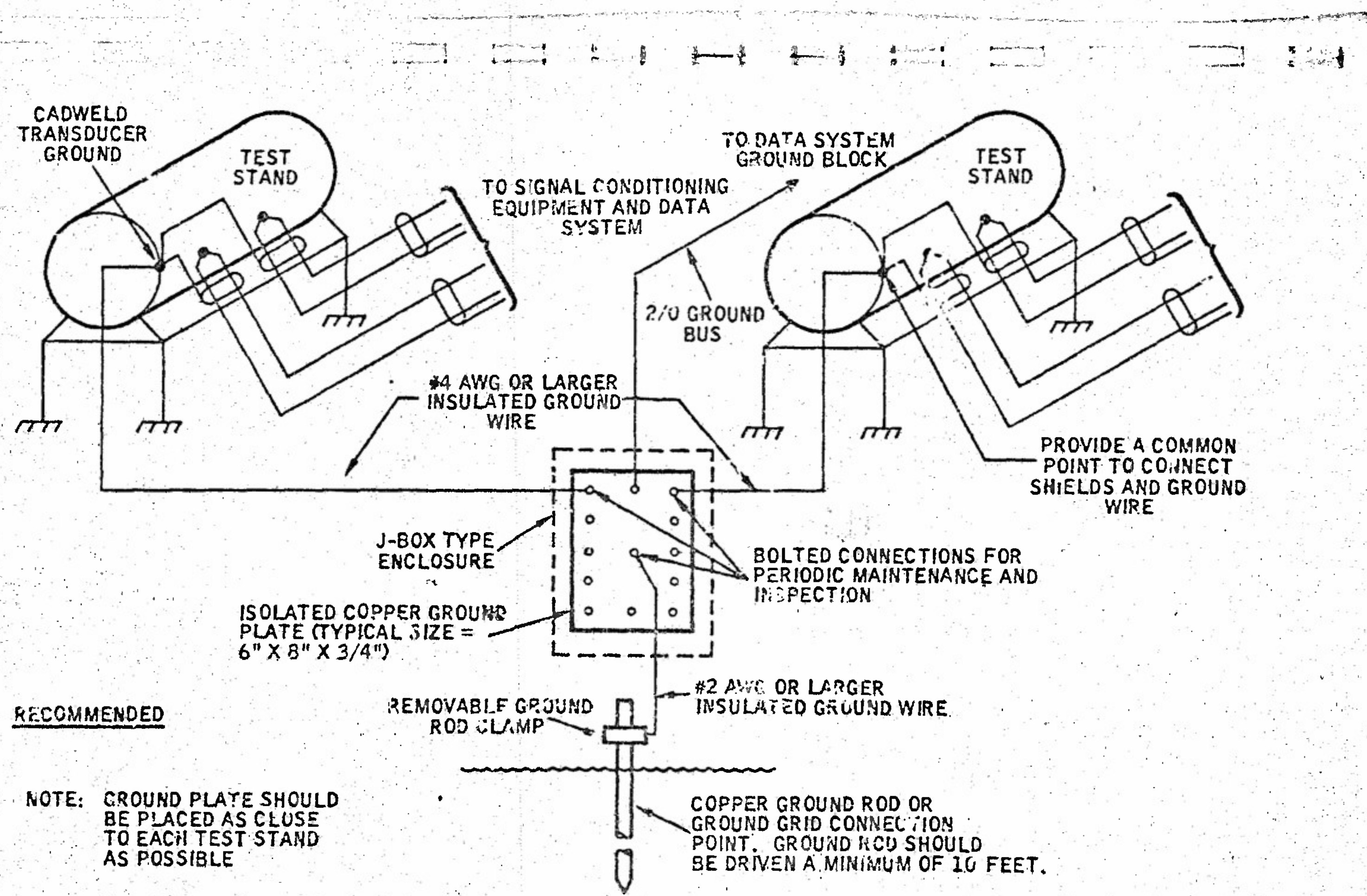


FIGURE 4-3
Typical Test Area Grounding Technique

4. Single-ended amplifiers can be used in digital data acquisition systems if channel-to-channel isolation is provided, (e. g. floating loads such as galvanometers)

5. Single-ended amplifiers should not be used with grounded (bonded) thermocouples to avoid channel-to-channel ground loops

6. Single-ended amplifiers should not be used with grounded bridges to avoid shorting one leg of bridge to ground

7. Connect cable input shield to:

   a) Test stand ground whenever possible

   b) Amplifier input ground if connection to test stand is impossible.

b. Grounding Rules for Using Isolated Differential Amplifiers

1. Guard shield of amplifier should be connected to input cable shield and cable shield earth grounded only at the transducer ground.

2. Connect chassis ground to system ground bus (plate)

3. Connect amplifier output guard shield to system ground bus (plate)

4. Do not connect input cable shield to earth ground, only to guard shield

5. If a permenant unavoidable instrumentation ground exists at the test stand as well as at the data system, use isolated differential amplifiers to break the ground loop

6. If a floating transducer is used, connect cable shield to amplifier guard shield and earth ground cable shield to test stand ground.

4.3 RECORDING, DATA ACQUISITION EQUIPMENT

The devices commonly used for recording and data acquisition are listed below:

a. Digital A/D system with digital magnetic tape, punched paper tape, or printer output

b. Analog or FM Magnetic Tape

c. Oscillographs

d. Strip Chart Recorders

e. X-Y Plotters

The treatment of grounding systems with respect to these recording devices for minimization of noise should be performed in compliance with the principles set forth in preceding sections of this handbook.

4.3.1 DIGITAL A/D SYSTEM

Unquestionably, the digital system is most susceptible to noise, because of the high resolution and accuracy which these systems offer (in the order of 0.01%). Grounding and noise reduction in digital systems must be in accordance to the following procedures (for more detailed information refer to Section 2):

a. Use thickest available insulation on all digital wiring

b. Twist all clock wires and long signal wires with a ground wire

c. Wire all digital circuits using shortest wire length possible. Use point-to-point wiring

d. Provide as many ground return paths as possible in all digital circuits

e. All ground wires must converge to system common ground point

f. Maintain maximum distance between digital circuits and low level circuits

g. Never connect analog grounds in such a manner that will cause any analog circuit to share a common ground return path with a digital ground return path.

4.3.2 ANALOG OR FM MAGNETIC TAPE

Magnetic tape is frequently used for high frequency data recording above 5 KC data. These systems are mostly single-ended and should therefore be subjected to much the same grounding practices as recommended for digital systems. Earth ground should be made at the test stand area with a single 2/0 or 4/0 cable making connection to the isolated grounding plate within the tape cabinet. Should the tape channels receive data in parallel with other single-ended channels such as an A/D system then special care must be taken to minimize the effects of inherent loops. A recommended dual recording scheme is shown in Figure 4-4.

The optimum method of recording two single-ended devices in parallel from the same data channel is to use isolated amplifier outputs. This means that the amplifier used for a given data channel will have dual outputs, one isolated from the other. This technique breaks the inherent loop and thereby decreases the noise which may result.

4.3.3 OSCILLOGRAPHS

Oscillographs are unique recording devices when grounding is considered because by nature they can provide isolated differential input channels. Each input channel of an oscillograph is comprised of a galvanometer circuit. This is simply a fine coil of wire to which a light deflection medium is affixed. A typical galvanometer circuit is shown in Figure 4-5.

a. Note that the galvo has no ground connections and, therefore, provides a reasonable degree of channel isolation. This means that provided galvo

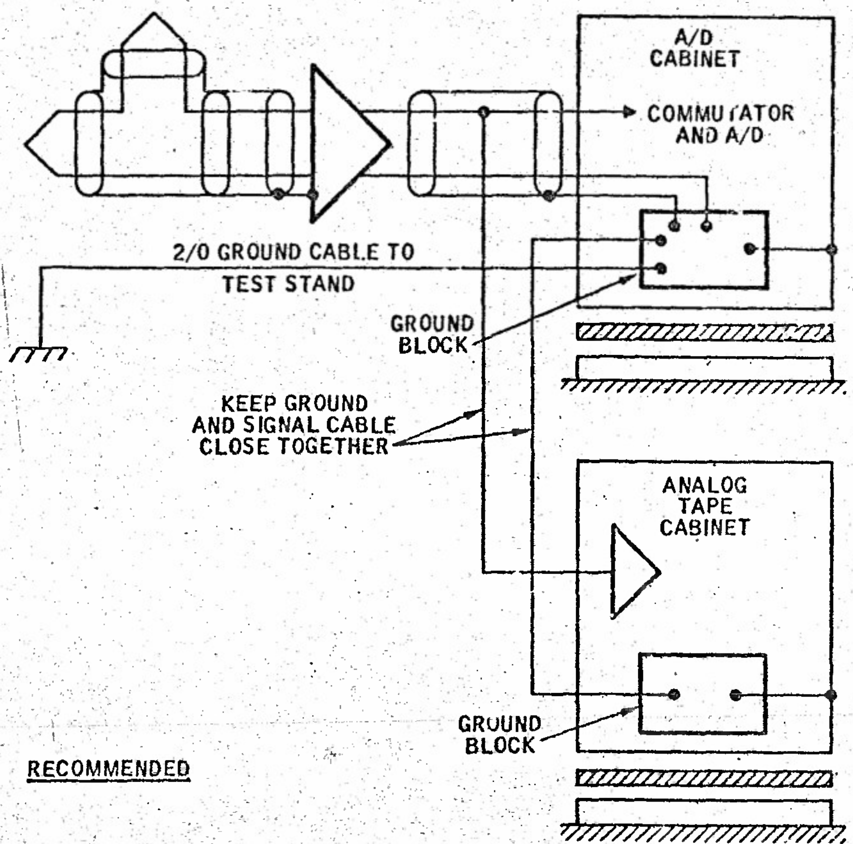


FIGURE 4-4
Two Single-Ended Recording Devices Connected in Parallel

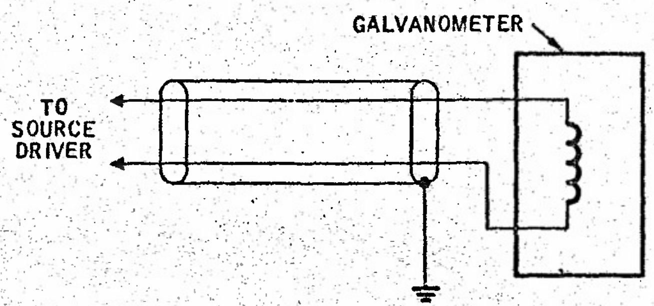


FIGURE 4-5
Typical Galvanometer Circuit for an Oscillograph

impedance is not so low that it loads the signal source driving capability, it may be connected in parallel with most single-ended devices and contribute no loop effects.

b. The shield can, in most galvanometer channels, be grounded either at the oscillograph or left open and grounded at the same point as the shield for the primary recording channel.

c. If the galvanometer is not connected in parallel with another recording device, the shield and galvanometer low side should be connected together at the oscillograph and this connection carried to the system grounding block.

d. The oscillograph, as all recording equipment, should be isolated except for its connection to the isolated cabinet and hence to the grounding block.

4.3.4 STRIP CHART RECORDERS

Strip chart recorders are mostly single-ended devices. Because of this, some basic factors should be emphasized. When using a strip chart as the only recording device for a given channel, the channel may be connected directly into the recorder as shown in Figure 4-6.

When another system is connected in parallel with a strip chart recorder channel, a more complex situation exists. Since the strip chart is a nulling device, its input impedance will change while it deflects from one position to another. This impedance change and an accompanying voltage feedback can be coupled directly from the strip chart input over to the input of a parallel recording device such as an A/D channel. Gross error can result in the A/D system. This difficulty can be resolved by using resistive isolation as shown in Figure 4-7 or by employing dual amplifier outputs, one for each recording device, as described for analog tape systems above.

4.3.5 X-Y PLOTTERS

X-Y plotters are provided in either digital or analog input configurations. The digital type plotters are usually connected as peripheral devices to computers or A/D systems and are grounded in accordance with recommended digital practices presented in Section 2.

Analog type X-Y plotters are normally single-ended and should be grounded and connected in the same manner as described for strip chart recorders above.

4.4 SYSTEM ISOLATION

Isolation from an overall systems viewpoint is included in Section 2, Paragraph 2.2.4. However, power isolation will be described in the following paragraphs so that its importance may be better illustrated. Isolation, as it applies to an instrumentation system, is the physical separation of the facility power system from the instrumentation power system, and the separation of susceptible areas from noise generators. Associated with power isolation is the separation of power grounds in each system.

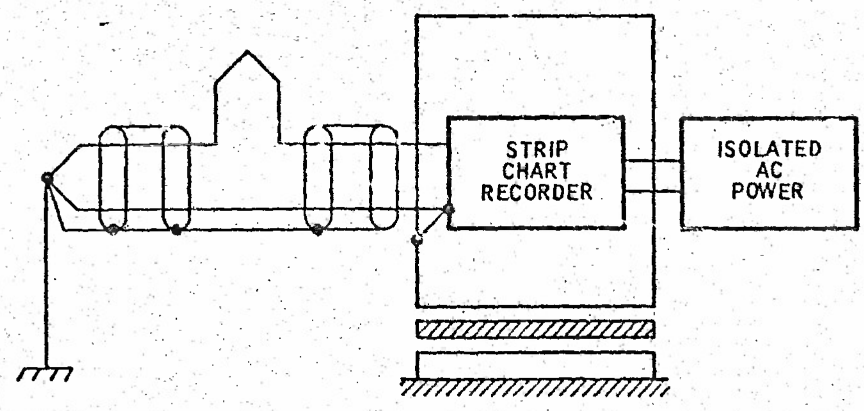


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FIGURE 4-6

Single Channel into Strip Chart Recorder

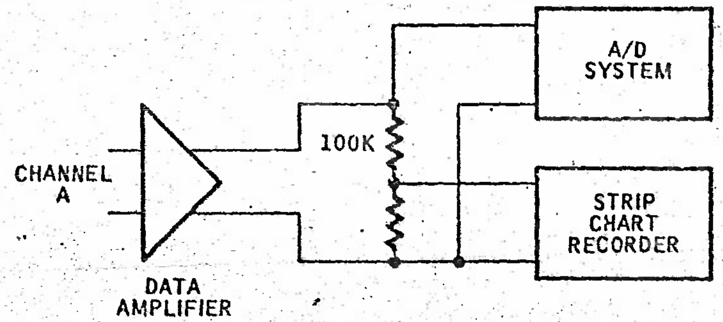

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FIGURE 4-7

Resistive Isolation of Strip Chart Channel from A/D Channel

4.4.1 POWER ISOLATION

The facility power system when used to supply power to a test facility carries with it two types of ground circuits. One ground circuit is called the power neutral and is part of the main current supply. The power neutral is a current carrying circuit as illustrated in Figure 4-8. The voltage on this line with respect to earth will be zero but the current supplied to the load must return to the generator, thus the current in the line will not be zero. The other ground circuit associated with the facility power system is the equipment ground. Its purpose is to offer a very low impedance path to earth from all metal enclosures and housings for fault currents caused by accidental shorts, insulation breakdown, or lightning surges, etc.

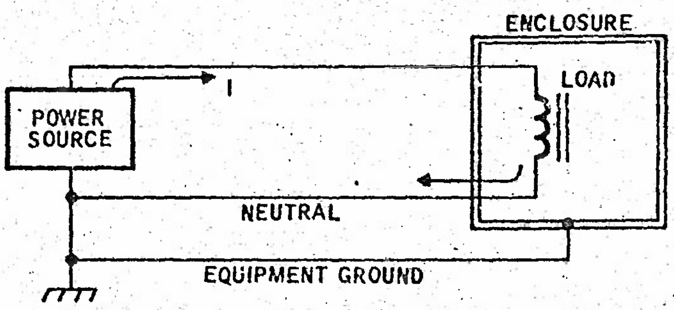

FIGURE 4-8
Power Neutral Circuit

During normal operating conditions this ground circuit will not have current flowing through it.

Each of these grounds is usually connected to earth at the primary power distribution point such as a sub-station or a stepdown transformer. A common-mode voltage can be formed between this power ground and the instrumentation ground when the two ground systems are connected together. This may result in large 60 cycle potentials in the equipment cabinets as well as in the data system ground. For more information concerning the common-mode generator, refer to Section 2, Paragraphs 2.1 and 2.2.

By properly isolating power from the instrumentation system, the effect of the common-mode voltage between the power system ground and instrumentation system ground can be eliminated. A box shielded isolation power transformer must be installed between the instrumentation system and the power distribution point. Figures 4-9 and 4-10 illustrate two similar systems, one without an isolation transformer and the other with an isolation transformer.

4.4.2 EQUIPMENT ISOLATION

The use of power isolation transformers will not completely provide cabinet isolation from ground. The following procedures are required to complete system and power isolation:

a. Use non-conductive material for conduit from cabinets to junction boxes, cabinet to base fasteners, etc

b. Use fiberglass insulation sheets between data system cabinets and the floor

c. All externally grounded equipment must not be in contact with data system cabinets

d. Use rigid steel conduit for all AC power cabling inside data system cabinets

e. Insulate data system ground plate from cabinet by fiberglass sheets

f. Connect all equipment cabinets to system ground plate via band straps

g. Connect system 2/0 or 4/0 ground bus to ground plate and carry ground bus to test stand earth ground point

h. Twist all AC power circuits inside data system cabinets.

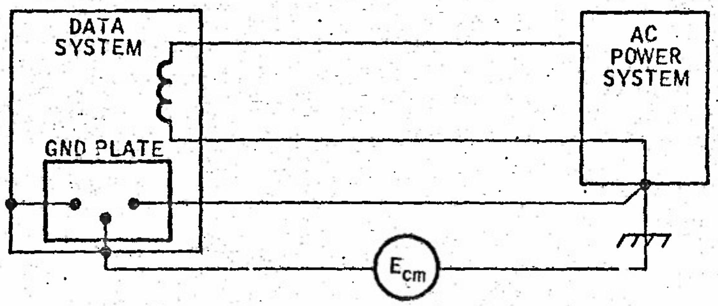

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FIGURE 4-9

Instrumentation System Without Isolation Transfer

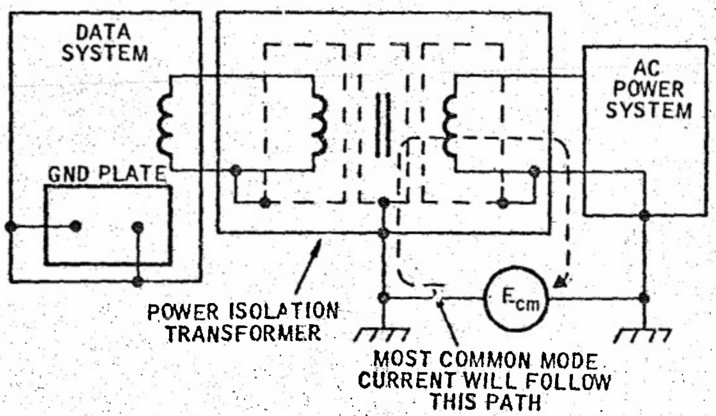

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FIGURE 4-10

Instrumentation System With Isolation Transformer

4.4.3 TEST AND INSTRUMENTATION AREA ISOLATION

Using a single point earth ground system for instrumentation and data acquisition will provide minimum interference from ground potentials. However, if the data

system is not carefully monitored, accidental shorts and insulation failures will cause unwanted ground loops. The following procedures are designed to maintain a data system free of unwanted contact with ground.

a. Use test stand ground and connect a 2/0 to 4/0 AWG insulated ground bus firmly to it

b. Carry ground bus to recording area and connect to data system isolated common ground bus or plate

c. Provide complete data system cabinet isolation above ground with fiberglass sheets, nylon bolts, etc

d. Connect all input instrumentation cable shields only to test stand ground. Amplifier output shields must be grounded to data system ground

e. An AC data system with unavoidable grounds at test area and recording area, AC shielded isolation transformers are maybe required to prevent earth ground loop between the two areas as shown in Figure 4-11.

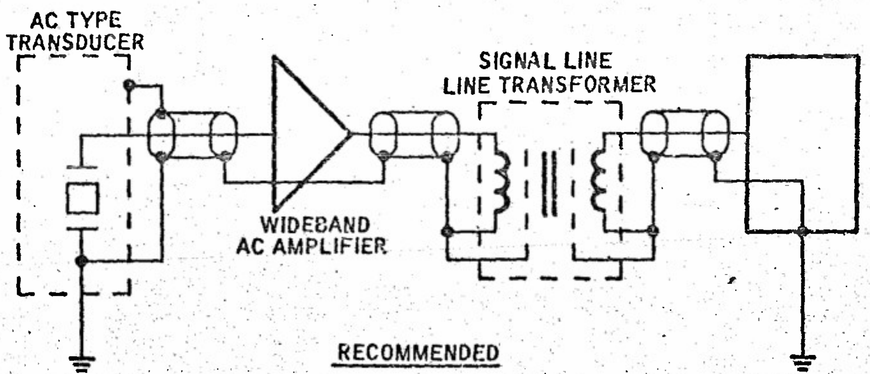

FIGURE 4-11
Shielded Isolation Transformers

4.5 CABINETS AND STRUCTURES

Cabinets, cable trays, power ducting etc. should be designed so that they can be properly grounded to an appropriate ground system.

a. Completely isolate all data system equipment from the local or blockhouse ground and have it tied to the grounding system located at the test stand in use

b. All data system cabinets within the blockhouse must be isolated

c. Where the above is not practical, all data system cabinets should be connected to a common ground bus system within the recording room or blockhouse

d. A large ground bus must be provided to connect all cabinets together to the ground bus system

e. Cable trays and power ducts should be firmly bonded together and to ground

f. Cable trays and power ducts must never be in electrical contact with isolated data system cabinets

g. In the case where complete cabinet isolation is not feasible, a less effective, but workable approach would be to provide two separate ground circuits from the same ground point within the recording area:

   1. Power ground, used for the grounding of all cabinets and hardware

   2. Instrumentation ground, used only for the grounding of the instrumentation circuits (see Figure 4-12)*.

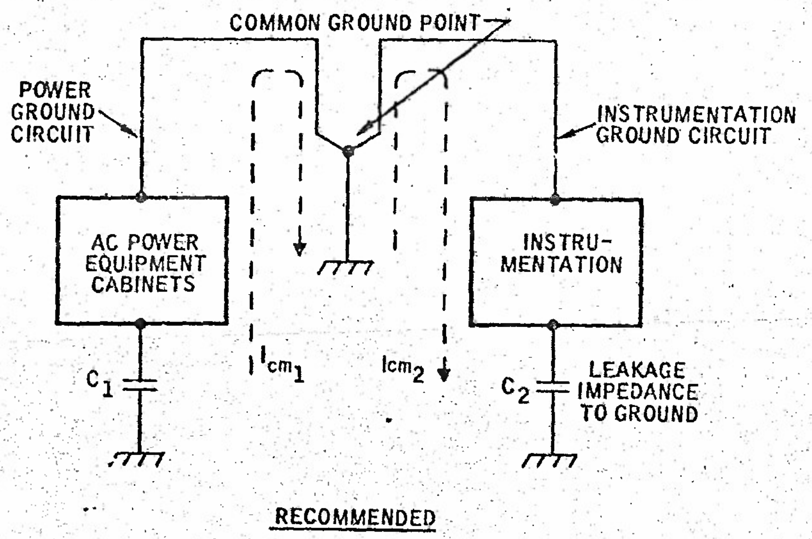

FIGURE 4-12
Simplified Dual Ground Circuit Configuration

4.6 COMMON GROUND PLANE

The common ground plane is the single earth ground connection area for the instrumentation ground, to be separate from the power ground if possible. Power grounding systems have not been included in this handbook since an abundance of

*The net result of this dual ground circuit is to allow AC power current to flow through a separate circuit and back to the power distribution system while the ground circuit used for instrumentation purposes is relatively free of such disturbances.

material exists on power system grounding techniques. Therefore, a more specific coverage is included relative to instrumentation system ground connections. For the purpose of this section "grounding" will be referred to as "earth grounding" unless otherwise specified. Figure 2-16 illustrates a typical system grounding design.

During the design phase of an instrumentation facility, both power and instrumentation grounding systems should be considered individually as well as in relationship to each other. Both grounding systems are divorced in application, but cannot be divorced in implementation, as both must be implemented during construction and steps should be taken to electrically isolate the two systems so that the instrumentation system will not be affected by the electrical power system. More information on this subject is included in Section 2 and the Bibliography.

The most important reason for grounding of any type of equipment is to insure that no voltages are present on accessible areas of equipment which will endanger the safety of personnel. In addition to safety, noise reduction and elimination must also be considered. This type of grounding is usually in the form of shield connections to ground, prevention of ground loops in the wiring, and provision of multiple ground paths in digital equipment. These grounding techniques have been discussed in detail in previous sections.

The following establishes a set of criteria for the proper technique of equipment grounding and the connection to earth ground:

a. All cabinets of the instrumentation system must be bonded together as illustrated in Figure 4-13

b. A ground wire (#10 stranded or larger) should be bonded to the cabinet and connected to the system ground plate

c. All subsystems mounted in the cabinet bays having swing-out or pull-out panels, doors, drawers, etc., should have a flexible ground connection from the movable module to the main chassis

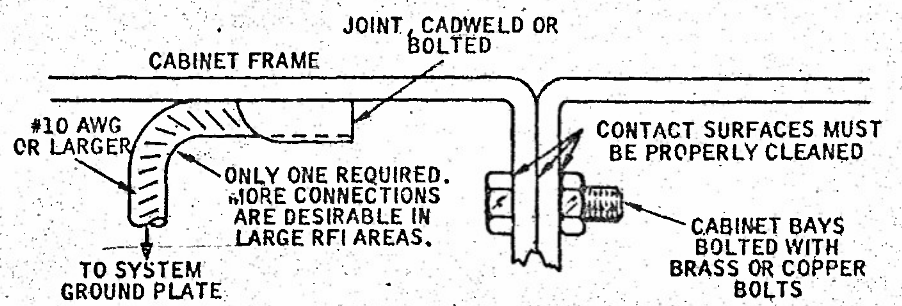

FIGURE 4-13

Detail of Cabinet Bays Bolted Together

d. If the input to the data system is single-ended, a second isolated bus can be provided to which the low side of the signal wires can be connected (see Figure 4-14). Adequate channel-to-channel isolation must be provided, such as commutation, isolated amplifiers, etc.

e. If channel-to-channel isolation does not exist, each shield ground and low side of each channel must remain separate so that ground loops are not formed between channels

f. The input ground bus must be connected to the system ground plate by a #10 or larger insulated ground wire

g. If the low side of the input signal wires are bused to a common point as shown in Figure 4-14, this point should be carried through the input device only and not connected to ground plate except at the load or A/D converter digitizer as shown in Figure 4-14

h. The ground plate should be mounted on fiberglass sheets, with nylon bolts if necessary, to isolate it from any unintentional ground. A large insulated ground wire, # 2/0 to 4/0 is bolted to the ground plate and carried to the test area

i. The test area ground plate should be located as close to the test stand as practical

j. Each test stand or cell should have a bonded ground strap of #4 or larger insulated copper wire running to the ground plate as shown in Figure 4-3.

Figure 4-15 illustrates a ground bus wire connected to a ground plate located in a test area. The ground plate serves as a common tie point for all ground wires connected from the test area instrumentation, such as shield and test stand ground straps.

Many test facilities with more than one test area may require simultaneous operation at each test area.

a. Connect the test areas together by using a heavy copper insulated wire carried to each test area ground point as shown in Figure 4-16

b. One variation to this method is connecting each test area ground bus to a common isolated tie point located between the test areas and carrying a single bus wire to the data system as shown in Figure 4-17

c. It is important that the impedance between the two test area ground points remain as low as possible so that the common-mode currents will be restricted to the grounds between the test areas, and not between the test areas and data system.

Where multiple test areas are a part of a test facility it is common that only one test area will be used and simultaneous operation or data acquisition from both

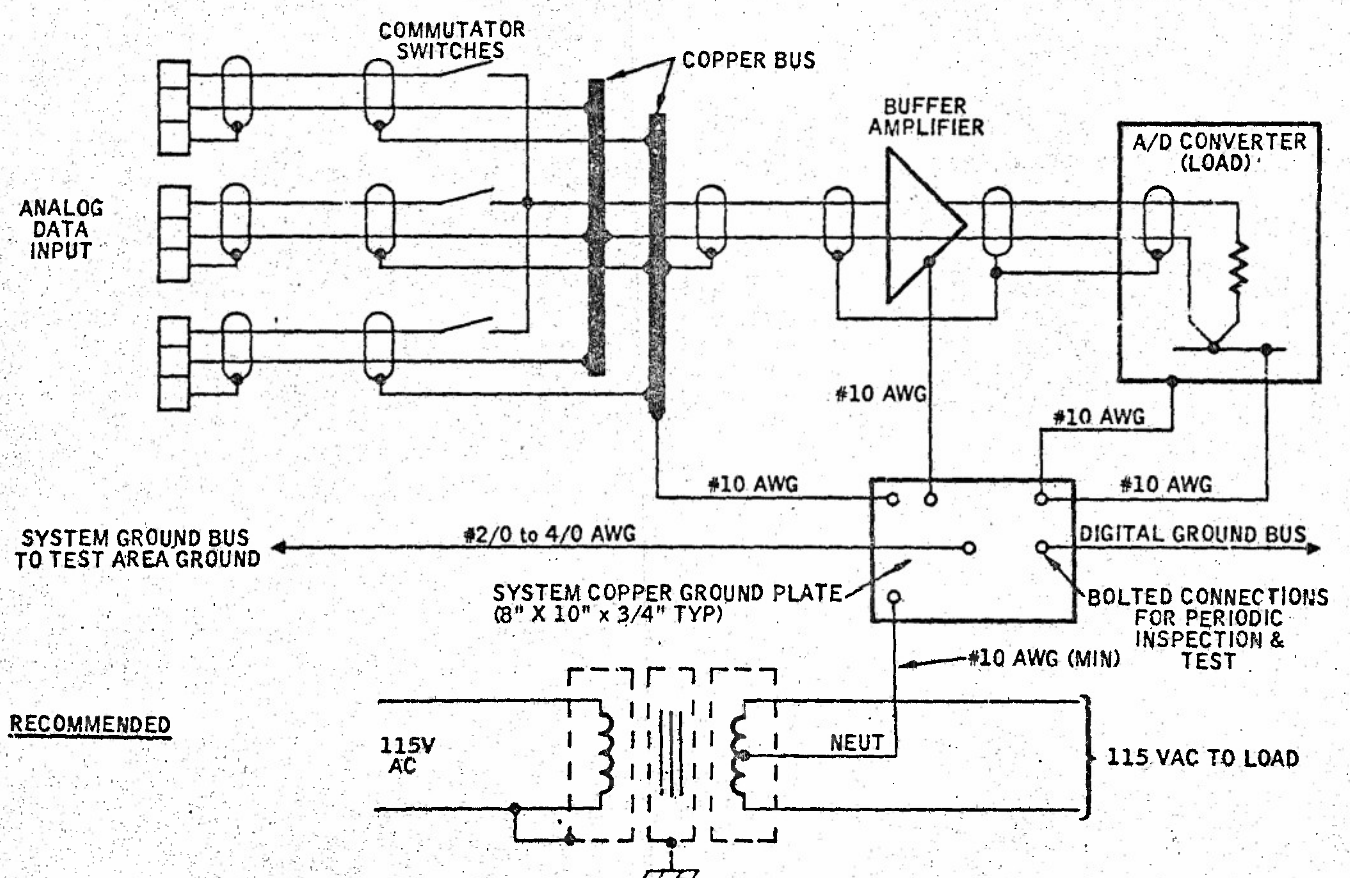

FIGURE 4-14
Typical Data System Grounding Technique

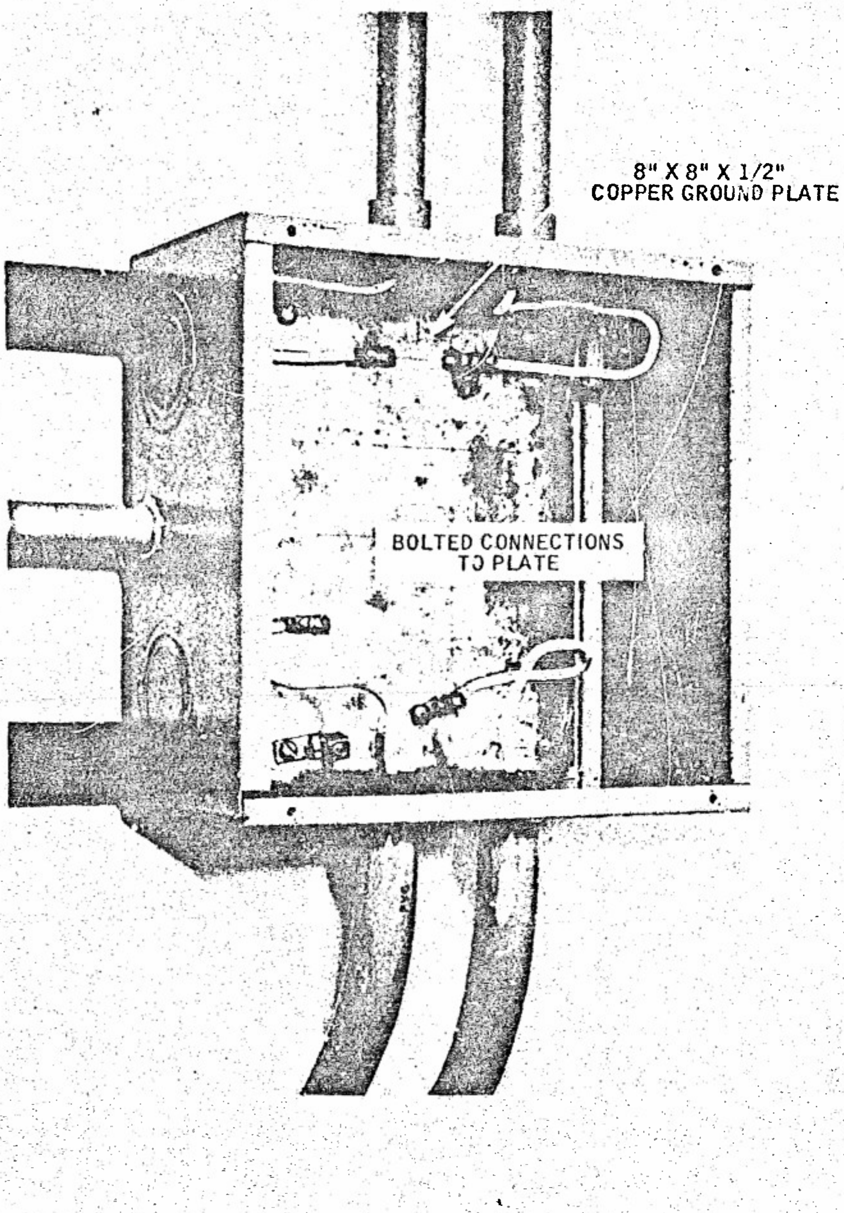

FIGURE 4-15.
Typical Ground Plate Installation in Test Area

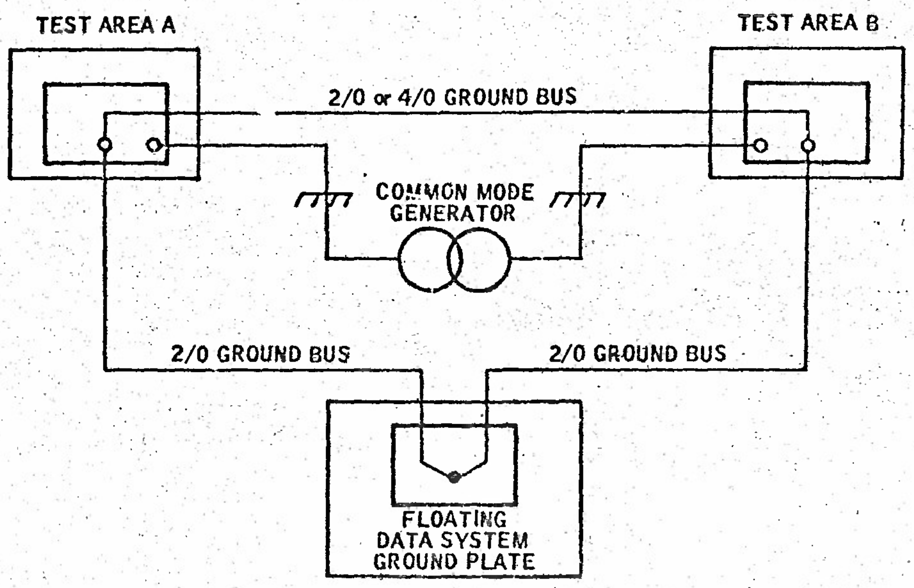

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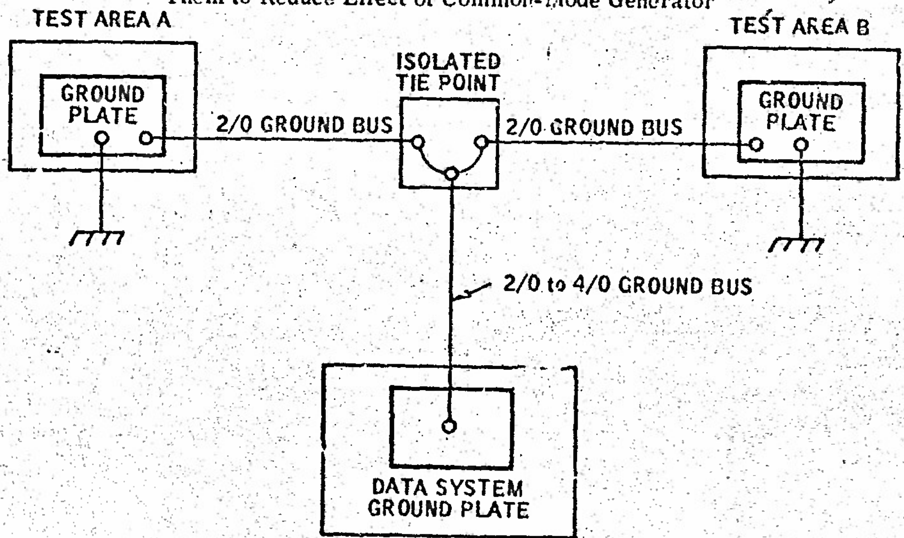
FIGURE 4-16

Two Test Areas with Heavy Ground Wire Connected Between Them to Reduce Effect of Common-Mode Generator



RECOMMENDED

FIGURE 4-17

Two Test Areas with Ground Bus Wires Connected to an Isolated Tie Point

test areas is not required. Each test area should have an earth ground point. In order to eliminate the common-mode generator between the test areas, the ground connection between the test areas is broken with a switch. Thus, when one test area is being used the other one is completely isolated from the data system. This switch may be a heavy duty manual knife switch or mercury relays automatically controlled from the data system area. Figure 4-18 illustrates a typical two test-area configuration using switched ground buses to the data system. Note that by using relays, an added safety protection can be utilized which knife switches cannot offer. By connecting one normally-open and one normally-closed relay for grounding, a ground connection is insured even in the event of power failure.

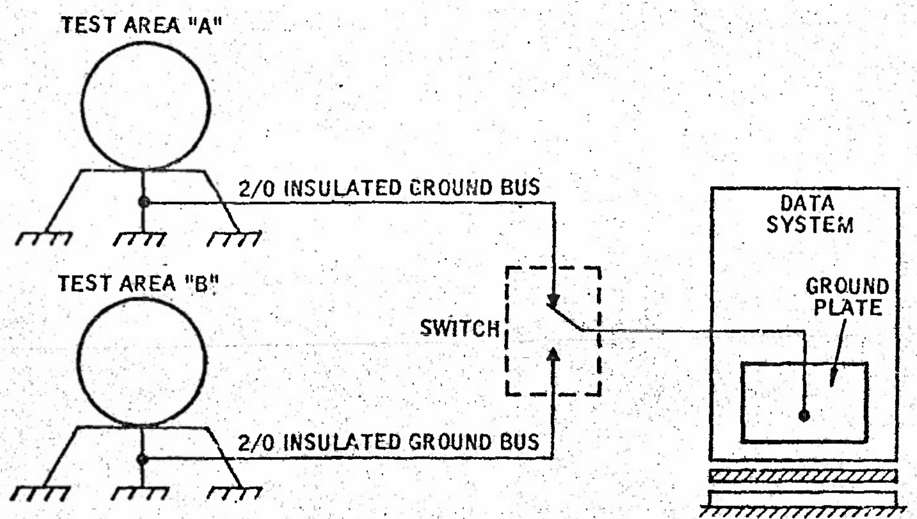


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FIGURE 4-18
Two Test Areas Using Switched Ground Buses to Data System

5. OPERATIONS, MAINTENANCE, AND MODIFICATION

The information included in this section is intended for the general use of instrumentation technicians whose job function is to operate, maintain, and modify existing instrumentation equipment.

In previous sections, grounding and noise reduction techniques have been discussed in detail regarding the overall instrumentation system as well as the components or subsystems. When these techniques have been thoroughly considered and a grounding philosophy has been established and implemented into a system it becomes a responsibility of the instrumentation technician to follow the system grounding techniques and rules to the fullest extent. Before changes are made to the basic grounding design of an existing facility a thorough check should be made in order to determine the extent of the problem and whether or not all grounding rules have been followed. Signal patching using plugboard type patching is a common source of ground loops. These patchboards should be clearly labeled and carefully checked before each data run.

5.1 NOISE MEASUREMENT

In order to present recommended methods of noise deflection and measurement, a typical A/D system is used as a model. The discussions which follow apply to this typical system and applicable measurement techniques which have been successfully used in the field (see Figure 5-1).

With any noise measurement, two important parameters to be remembered are:

a. peak-to-peak noise amplitude
b. frequency of the major noise components

These two parameters are difficult to measure with a digital system because of its characteristic as a sampling rather than a continuous monitoring device. The RMS value of the noise signal will be of little significance. The analog-to-digital converter in a typical digital system will read peak-to-peak amplitude. Knowing the frequency of the major components of the noise will point to the cause. For example, if 60 cycle is present it would point toward the power ground system. If 120 cycle is present it would point toward power supply ripple. Most digital data acquisition systems limit the input data frequency to approximately 500 cycles or less. Therefore, high frequency noise present on the data input lines to the system is not carried through to the A/D converter. Any high frequency noise present at the input of A/D converter is usually generated within the data system. The most common approach to the detection of the noise

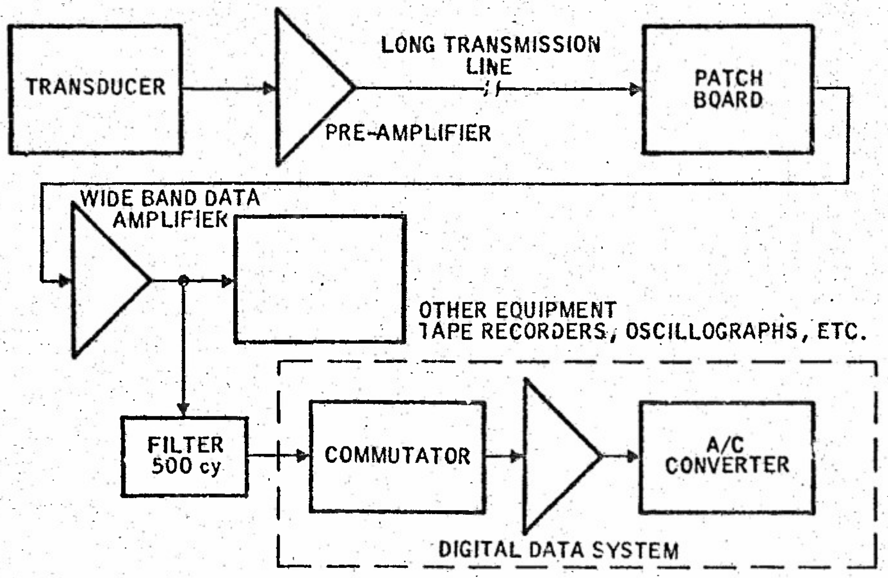


FIGURE 5-1
Typical Data Acquisition System

generator is to start at the output, usually the A/D converter and work toward the input. The most convenient piece of test equipment used to make noise measurements is the oscilloscope.

5.1.1 EQUIPMENT

The requirements for an oscilloscope to make noise measurements are as follows:

a. High-gain vertical pre-amplifier
b. Wide band
c. Floating differential input
d. Power line isolation to the scope

If the scope does not have a floating differential input and the case is connected to power ground the scope will introduce noise into the system under test. Any noise measurements made under these conditions will not be valid. Isolating the scope from power ground by means of a Faraday shielded isolation transformer will insure proper isolation and also eliminate the possibility of shorting out any inputs while making differential measurements.

The main advantage to using an oscilloscope for noise measurements is that it gives a graphical representation of the noise showing both peak-to-peak amplitude and frequency. Since the oscilloscope displays all frequencies within its bandwidth at one time it is sometimes difficult to pick out the major frequency

components of the noise. One approach to solving this problem is to use a spectrum analyzer in order to separate the noise into its individual components. Another approach is to use a variable-bandpass filter in front of the oscilloscope. The same requirements for power-line isolation apply for all pieces of equipment used in the noise measurements.

5.1.2 MEASUREMENT OF NOISE

Figure 5-1 shows a hypothetical system on which the noise measurements will be made. Figure 5-2 shows the oscilloscope configuration used to make the noise measurements. Noise measurements are performed in the following manner:

a. The vertical input to the scope should be shielded wire.
b. The amount of exposed wire at the probe end should be kept to a minimum.
c. First check to be made is to short the scope probes together to measure the inherent noise of the scope. The inherent noise of the scope must be very small when compared with the noise to be measured.
d. The scope should be connected across the input to the A/D converter. It will be necessary to trigger the scope from the "digitize" command.
e. The sweep time should be set to coincide with the analog-to-digital conversion time. (For most high speed systems a time base of 10 microseconds per division will be sufficient)
f. The scope now displays the noise which the A/D converter receives. Any noise present at times other than the digitizing time will have no effect on the digital output. Noise present on a single sweep of the scope would most likely be caused by a sample-and-hold amplifier, the A/D converter, or the digital commands between the two. Any variation of signal amplitude from sweep-to-sweep of the scope (assuming system input constant) will most likely be caused by circuitry ahead of the A/D converter.
g. If the noise is found to be forward of the A/D converter, connect the scope across the input of the sample-and-hold amplifier.

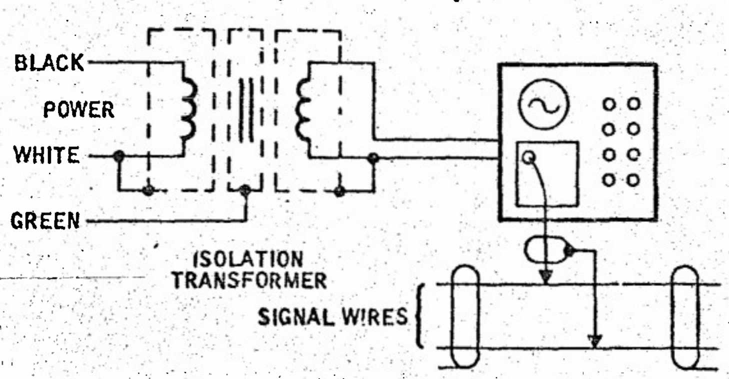


FIGURE 5-2
Noise Measurement Configuration

h. Trigger the scope from the commutator drive pulse; if the digital data analysis showed individual channels, rather than all channels to be noisy, one of the noisy channel drive pulses should be used, otherwise any channel drive pulse can be used.

i. The sweep time should be set to coincide with the sample time. For most systems a time base of 5 USEC per division will be sufficient.

j. Record the value of noise present. A scope camera would be useful for this purpose.

k. Disable commutator operation and place a jumper from the commutator input to output.

l. Record the value of noise. A difference between this value and the previous value would indicate that the noise is generated by the commutator. Possible causes of noise in the commutator could be malfunctioning commutator switches, improper signal and shield termination, or power supply noise pickup.

m. If the noise is found to be forward of the commutator, move the scope probes to the output of the filter.

n. The scope should be triggered internally. There should be no noise present beyond the bandpass of the filter.

o. From this point on the easiest approach to the detection of the noise generator is to leave the scope connected to the output of the filter then break a connection and apply a short across the line. Using this technique, work toward the transducer. The point at which the noise increases indicates that the noise generator is located between this point and the previous point.

Another useful tool in the determination of noise accepted by the A/D converter of a digital system is a resistive ladder network. A simple four resistor circuit may be assembled in a matter of minutes,to permit the technician to make precise scope measurements of the actual digitized noise. Figure 5-3 illustrates the circuit and method of connection to the A/D system.

Five percent carbon resistors may be used and connected to the A/D or A/D display hold register (may be least significant bits if a binary A/D converter is used). After making the connection shown, perform the following steps:

a. Place the scope in DC input operation with a high sweep rate (10 microseconds/centimeter is sufficient.

b. The A/D [illegible]m is then placed in standby condition so that the A/D "units" hold register [illegible] manually set to the desired count values.

c. Step the units decade manually from "0" through "9". (Note the sweep rise on the scope face)

d. At each sweep position, a strip of masking tape on the face of the scope should be marked with the equivalent decimal setting of the decade. This calibrates the trace.

Now, if the A/D system is placed in normal operation, the least significant bits of each sample of the A/D converter will be shown on the scope since the weighted resistors perform digital-to-analog conversion. If the system input voltage is set to provide an average scope reading of 5 counts then the total "count spread" may be determined by the trace excursions above and below this value (provided count spread doesn't exceed 10 counts below 0 or above 9).

The D/A technique can provide very useful information in determining total accuracies of a digital system. If the hold register is gated for a selected channel, the noise for only that channel will be displayed, thus providing meaningful noise data on a per channel basis.

Digital system noise is usually specified as a percent of full scale. If full scale is 9999 (0000 through 9999 is 10,000 counts) and count spread is six counts (+3442 to +3448 for example) then the noise is 6/10,000 = 0.06% or ±0.03%.

5.2 SHIELD CONNECTION

The shield connection will be regarded with respect to instrumentation cable shields which originate at the transducer or test area and carried to the data acquisition system. The purpose of shielding is generally recognized as a means to prevent extraneous noise from interfering with sensitive signal lines. The most common cable shield is the braided copper shield. One other cable shield, aluminum foil, is becoming more popular because of its shield coverage, lower cost, and ease of handling.

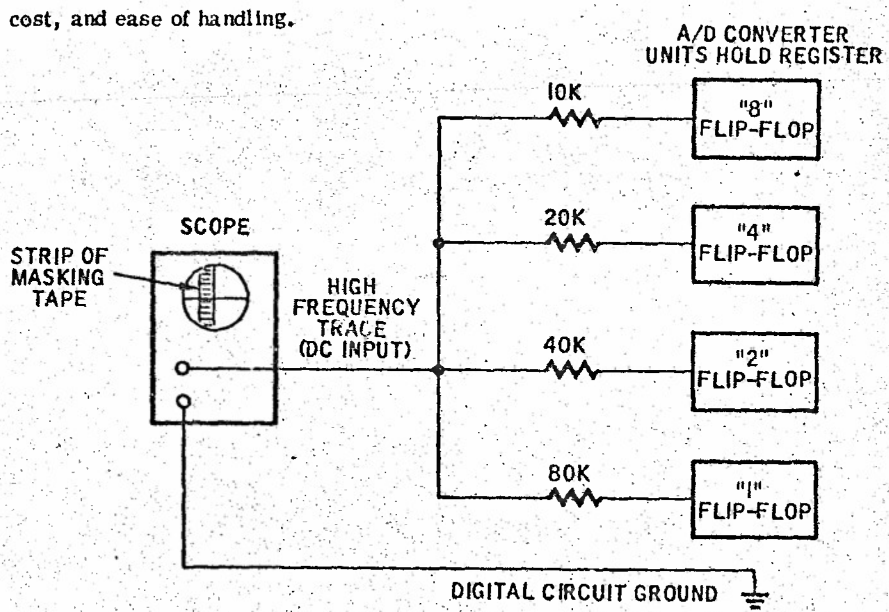
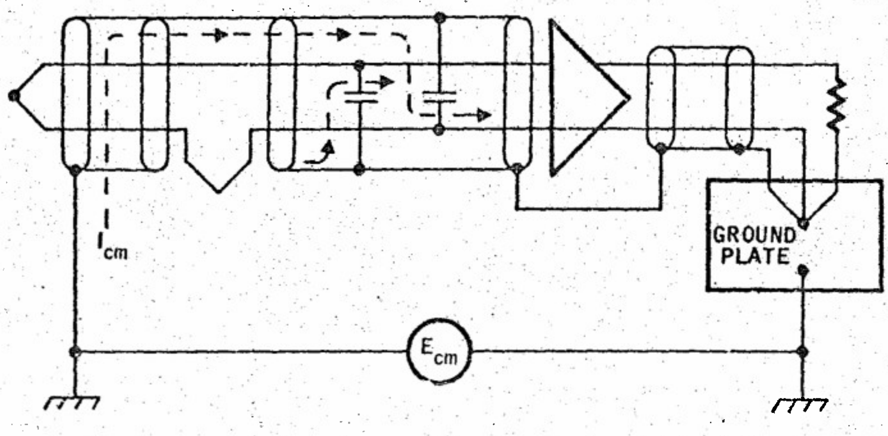


FIGURE 5-3
Digital Noise Measurement

Regardless of the type of shield used it is possible to cause more noise in the signal lines by improper grounding of the shields than the extraneous noise which is being shielded against. If a closed path is formed by the shield between two ground points a current will flow through the shield. If the ground connection is an earth ground, 60 cycle current will flow into the shield. The capacitance of the wire to shield will allow this 60 cycle earth current to be coupled into the signal wires as shown in Figure 5-4.



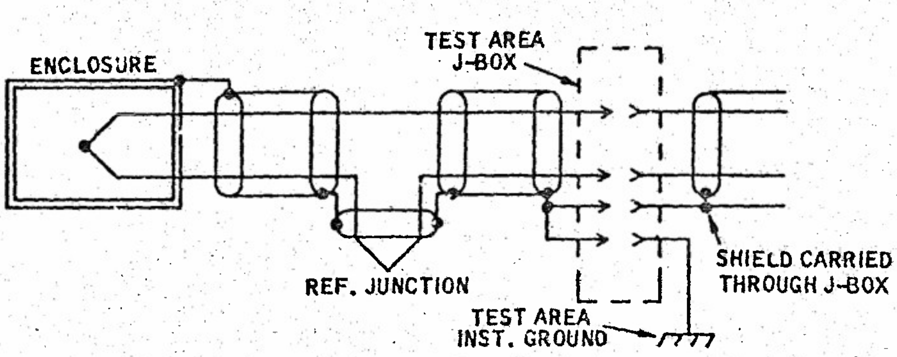
NOT RECOMMENDED

FIGURE 5-4
Shield Grounded at Two Earth Ground Points

Therefore, the underlying purpose in proper grounding of cable shields is to prevent ground loop currents and to provide a low resistance path to earth for extraneous noise pick-up in the shield.

As the signal levels of transducers are lowered the noise susceptibility of the transducer signal increases. In some test facilities where all data is being recorded for low accuracy "quick-look" type testing the reduction or minimization of noise is usually not emphasized. However, in a complex test facility where many channels of data are to be measured and where the pre-test set-up takes many hours or even days it is important that the most accurate and reliable data be obtained so that the test will not have to be repeated unnecessarily. Thus, every precaution must be taken to assure noise-free or near noise-free data.

Figures 5-5 and 5-6 illustrate the recommended method of properly grounding and terminating the cable shield at the transducer.



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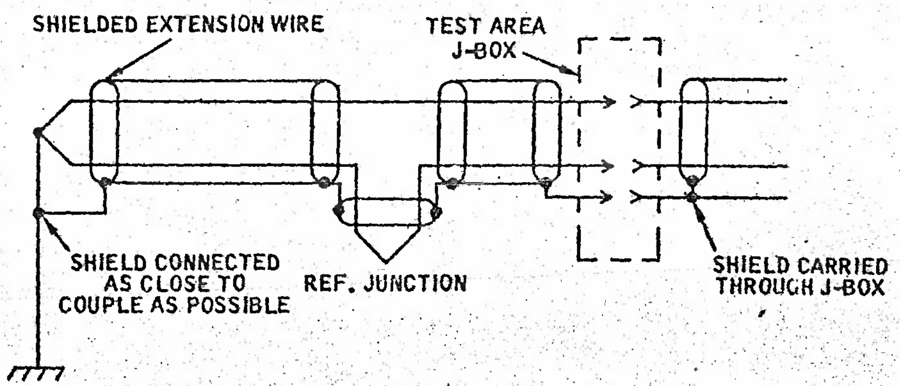

RECOMMENDED

FIGURE 5-5
Cable Shield Grounding Procedures to Minimize Noise Interference in Thermocouple Transducer Signals

Once the transducers have been connected into the signal line, the data amplifiers are then connected to the transducers. Generally there are two types of data amplifiers used in instrumentation:

a. Single-ended wideband AC amplifiers and,

b. Differential isolated DC amplifiers.

Figures 5-7 and 5-8 illustrate the proper grounding and shield connections for these amplifiers.

Single-ended amplifiers are most commonly used for wideband data measurements with AC type signals.

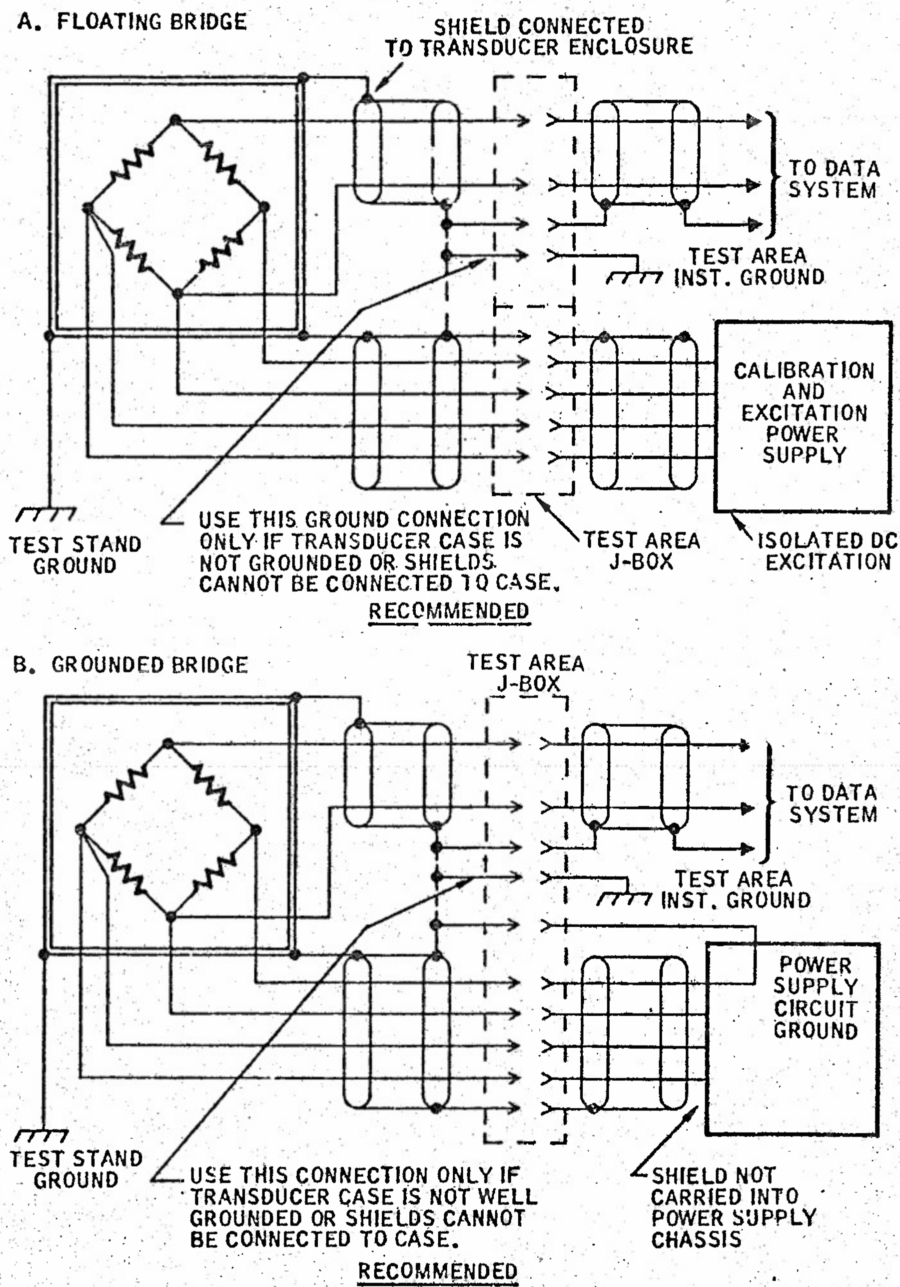

FIGURE 5-6
Cable Shield Grounding Procedures to Minimize Noise Interference in Bridge Transducer Signals

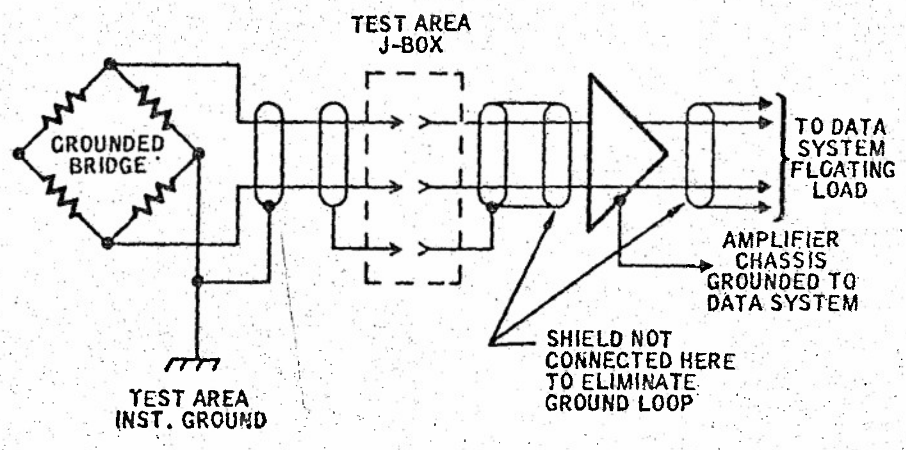

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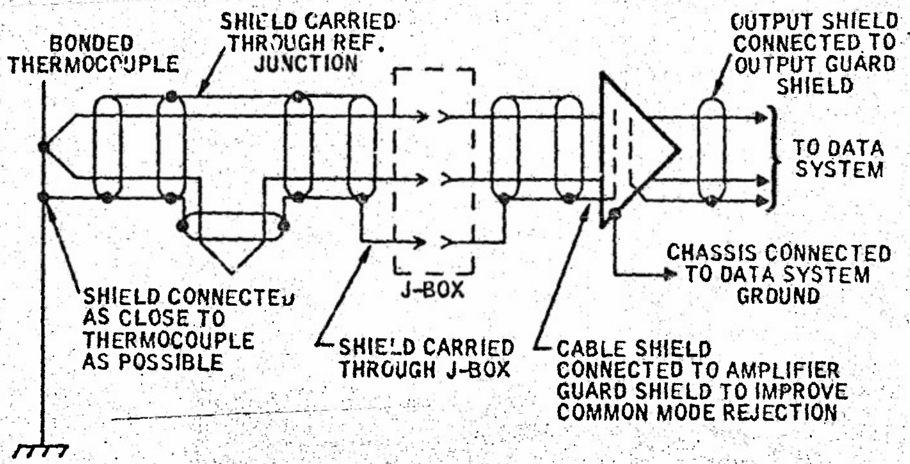
FIGURE 5-7
Shield Connections for Single-Ended Amplifiers

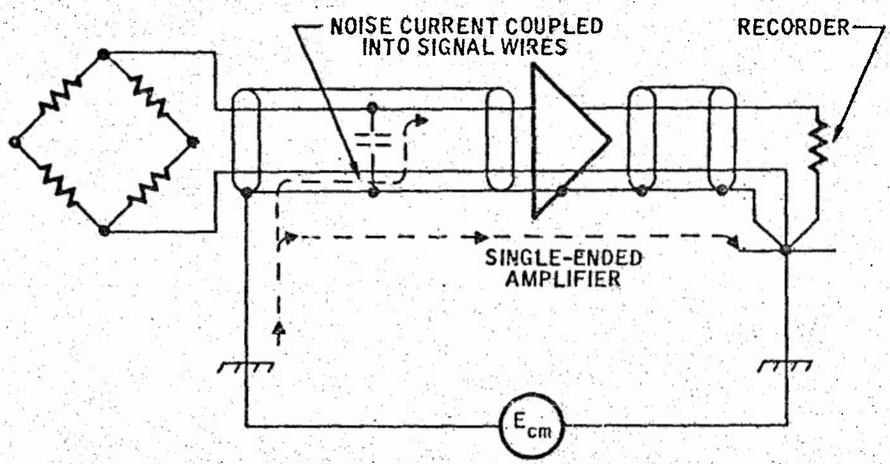


RECOMMENDED

FIGURE 5-8
Shield Connections for Differential Amplifiers

Isolated differential amplifiers are commonly used for DC slow varying signals such as thermocouples.

The use of single-ended amplifiers is required in many applications; therefore, it is necessary that all shield and signal wire connections be carefully considered and checked so that no ground loops are formed between test area and data system area. Figure 5-9 illustrates how a ground loop may be formed by improperly grounding of the shields.



NOT RECOMMENDED

FIGURE 5-9
Ground Loop Formed by Improper Shield Grounding

Another important consideration is that of forming channel-to-channel ground loops as shown in Figure 5-10.

To prevent these ground loops, install isolated differential amplifiers in place of single-ended amplifiers or install isolated DC excitation power supplies in each channel.

When grounding the instrumentation cable shields in the data system the following steps must be followed:

a. Grounded Transducers (see Figure 5-11A)

1. Do not connect cable shield to ground at the data system input if isolated differential amplifiers are not used in data line
2. Connect cable shield as close to transducer ground as possible
3. If signal drives load directly, load must be isolated from ground to prevent ground loops
4. Carry shields through all terminal boards.

b. Ungrounded Transducers (see Figure 5-11B)

1. Do not connect cable shield to data system ground, if isolated differential amplifiers are not used in data line
2. Connect cable shields and transducer case to single ground point in the test area
3. Provide test area ground point for grounded transducer case if case does not have solid ground connection
4. Carry all cable shields through each terminal block for the entire cable length.

c. Single-Ended Data Amplifiers (see Figure 5-12A)

1. Do not connect shield to amplifier input ground if transducer is grounded.
2. If transducer and transducer case are completely floating, connect cable shield to amplifier ground.
3. Do not connect amplifier output ground to output cable shield. Shield will be grounded to data system ground bus.
4. If a floating transducer is used, connect cable input shield to amplifier output cable shield to amplifier output ground.

d. Isolated Differential Amplifiers (see Figure 5-12B)

1. Never connect amplifier input cable shield to ground.
2. Connect input cable shield only to amplifier guard shield.
3. Amplifier output cable shield should be connected to amplifier output guard shield, if provided.
4. Amplifier input cable shield must be grounded only at the test stand transducer ground.

5.3 SIGNAL GROUNDS, EQUIPMENT GROUNDS, AND POWER GROUNDS

The ground circuits of a data instrumentation system are categorized as follows:

a. Signal Ground
b. Equipment Ground
c. Power Ground

Signal grounds are further classified into analog and digital grounds as indicated below:

a. The analog ground circuit begins with the transducer circuit ground and is carried up to the data amplifier, into the data system and to the input of the A/D converter.

b. The digital ground circuits are those ground circuits associated with the output of the A/D converter and carried throughout the logic circuits in the digital portion of the system.)

Equipment grounds are defined as those ground connections which are used to connect all equipment cabinets, chassis, panels, and enclosures to earth ground in order to prevent dangerous potentials and fault currents from occuring on the equipment. These grounds will usually be in the form of bonding straps, large copper wire connections between equipment cabinets, etc.

The power ground circuits are the ground and non-current carrying circuits associated with the AC power to the data system which is connected to earth. The power return is the neutral or low side of the AC power circuits which originates at the load and are carried to the transformer (see Figure 5-13).

The power ground is commonly connected to the center tap of the secondary and presents a safety path to earth for fault currents such as accidental short circuits in the AC power line.

5.4 GROUND LOOP PREVENTION AND DETECTION

As discussed in the previous section ground loops can be formed by improper connection of shields, signal wires, and amplifiers. The detection of ground loops in a signal path is not always simple, however the common ground loop signal in an instrumentation facility will be mostly a periodic noise function at 60 CPS

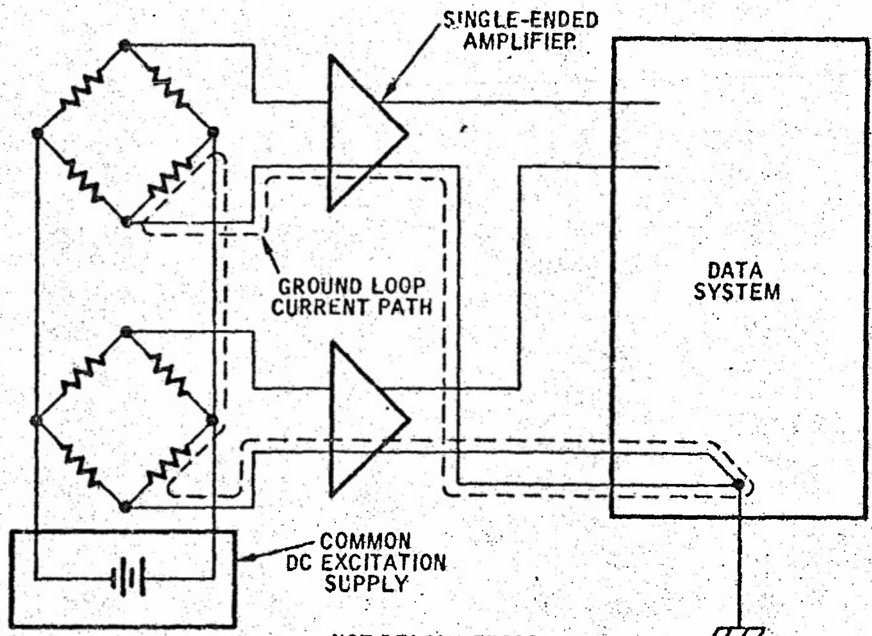
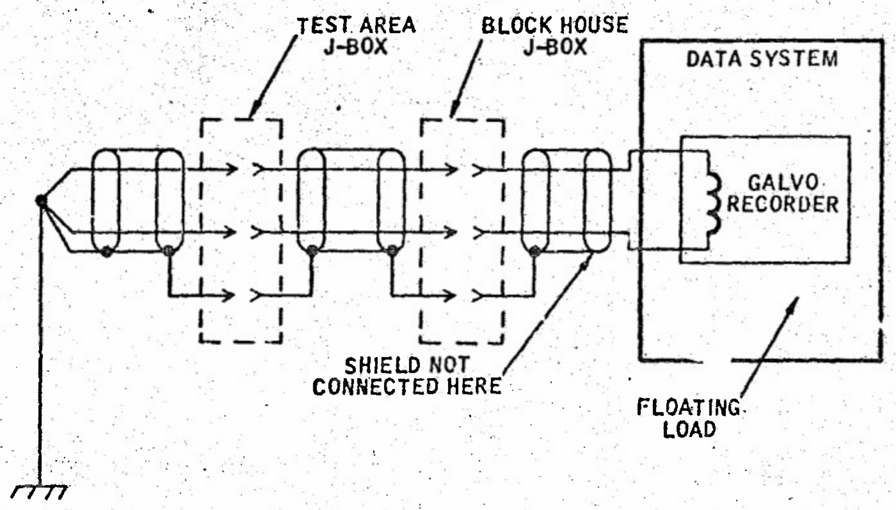


FIGURE 5-10
Ground Loop Current Channel-to-Channel Caused by Improperly Grounding of Single-Ended Amplifiers

A. GROUNDED TRANSDUCERS



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B. UNGROUNDED TRANSDUCERS

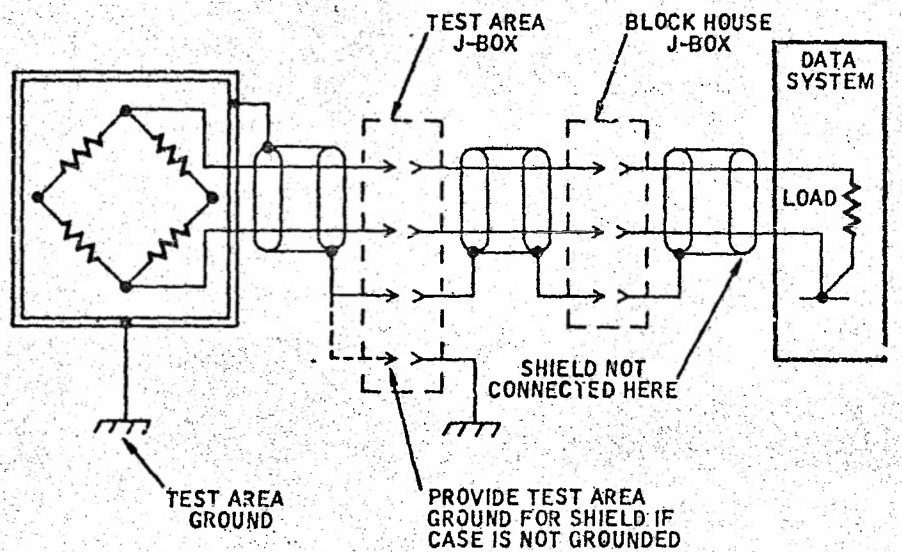

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FIGURE 5-11
Proper Shield Connections in Data System Input

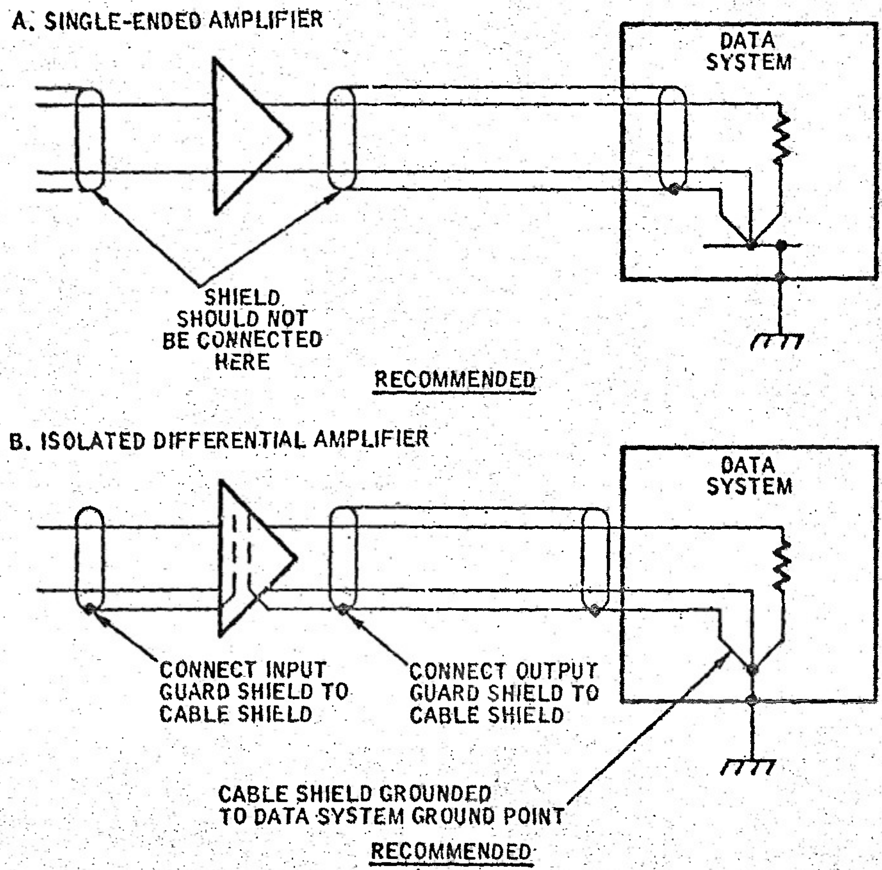

FIGURE 5-12
Proper Shield Connections in Data System Input

appearing on the signal lines. 60 cycle noise may have a large third harmonic as shown in Figure 5-14.

Single-ended amplifiers and recording equipment are a source of ground loop problems. To prevent ground loops from occuring the following procedure should be followed:

a. Cable shield should be grounded at only one point, preferably at the test stand.
b. If a floating transducer is used, the low side of the signal pair must be grounded at only one point.
c. If a grounded transducer is being used the amplifier output must be floating.
d. Using grounded transducers, connect cable shield as close to transducer ground as possible and do not connect shield to amplifier input.

e. Check for unwanted grounds by lifting shield from ground point and making a continuity check from shield-to-ground. If a short or low resistance is detected an unwanted ground exists and must be eliminated.

f. To check for unwanted grounds in data line, disconnect cable from transducer and load. Measure the low side signal line to ground. If continuity exists, an unwanted ground exists and must be eliminated

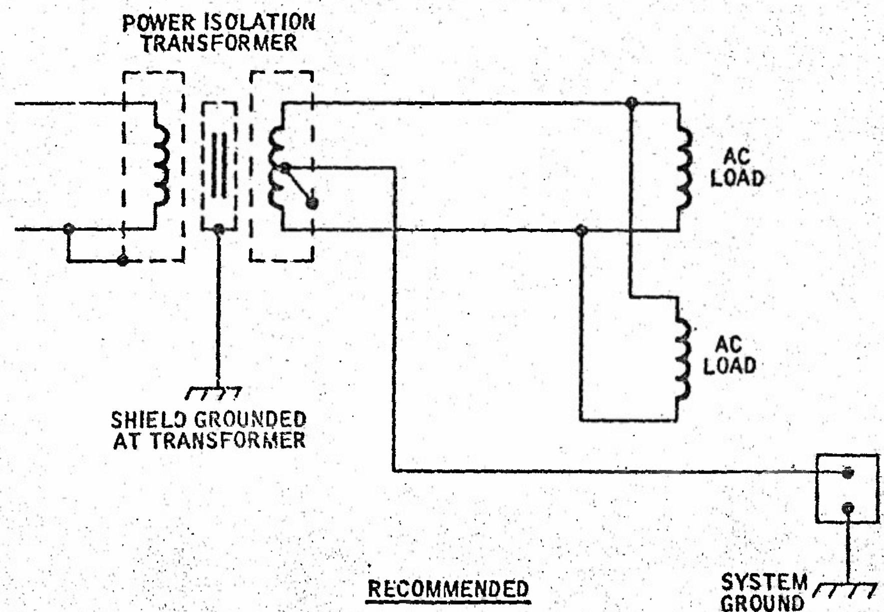

FIGURE 5-13
Typical AC Power Ground Wiring Configuration

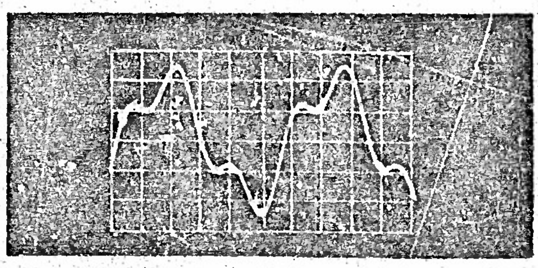

FIGURE 5-14
60 Cycle Noise With Third Harmonic Distortion

A ground loop may be formed whenever two or more different connections are made to ground where these connections are not at the same point. Ground loop currents can only be eliminated by breaking the closed (AC or DC) path - by providing only one ground point for all ground wires.

Perform the following procedures for detection and prevention of ground loops:

a. Where control circuits using ungrounded coils and ungrounded transducers are used whose enclosures are grounded, the cable shield should be connected to the enclosure and not at the input to the single-ended device. This technique is shown in Figure 5-15.

b. Where many channels are connected into a large terminal block near the test area it is recommended that a common isolated bus be provided to which all cable shields originating at the test area may be connected. This bus is then connected to the instrumentation test area ground point. If a transducer is grounded at some other point (such as a bonded thermocouple) the shield on that cable should not be connected to the common bus but should be connected to ground as close to the thermocouple as possible as shown in Figure 5-16.

c. When a common bus is used in the test area for grounding shields, the shields being carried into the data system must not be grounded at the data system. If a single-ended buffer amplifier is used in the line as shown in Figure 5-17, the shield should not be carried through the amplifier and the output shield should be connected to the data system ground.

d. A single-conductor shielded cable can produce ground loop currents if the shield is used as the ground return path of the circuit. This ground loop can be formed by the shield when the shield is a part of a metallic connector (BNC type) which is mounted directly to the metal case or enclosure as illustrated in Figure 5-17A.

e. The following ground loops and preventive arrangements should be considered in a system with several series elements:

   1. Transducers and amplifiers with one side of their signal circuit connected to their cases.
   2. Proper arrangement for isolating the low side and shields from individual chassis in order to open circuit ground loop currents.

f. Certain transducers are designed so that the case is part of the signal circuit. Among these are piezoelectric accelerometers. A ground loop can be formed if the shield is connected at the data system in addition to the case, as shown in Figure 5-18.

5.5 INSTALLATION OF GROUND RODS

As described in Appendix A, the soil resistivity in a given location will fluctuate according to its moisture content, temperature and depth. The importance of

maintaining a constant low resistance contact with the earth is significant when the ground connection is to be used for power fault current. If a resistance of sufficient magnitude exists in the ground connection, a considerable potential could exist on equipment enclosures, ground wires, etc., which would endanger the safety of personnel under fault current conditions.

In a data acquisition system which floats equipment cabinets above ground at the blockhouse or instrumentation recording area, a ground bus wire will be carried to a ground point, usually in the test stand area, where a low resistance connection to earth is established. Therefore, an instrumentation earth ground connection of minimum resistance is required for the safety of personnel, and does not necessarily contribute to noise reduction.

A ground rod earth ground system has advantages over other ground systems such as buried plates, buried strips, cables, grids, etc. Primarily the ground rod installations affords a lower cost as compared to the other forms of grounds. Simplicity of installation, minimum area requirement, plus installation can be

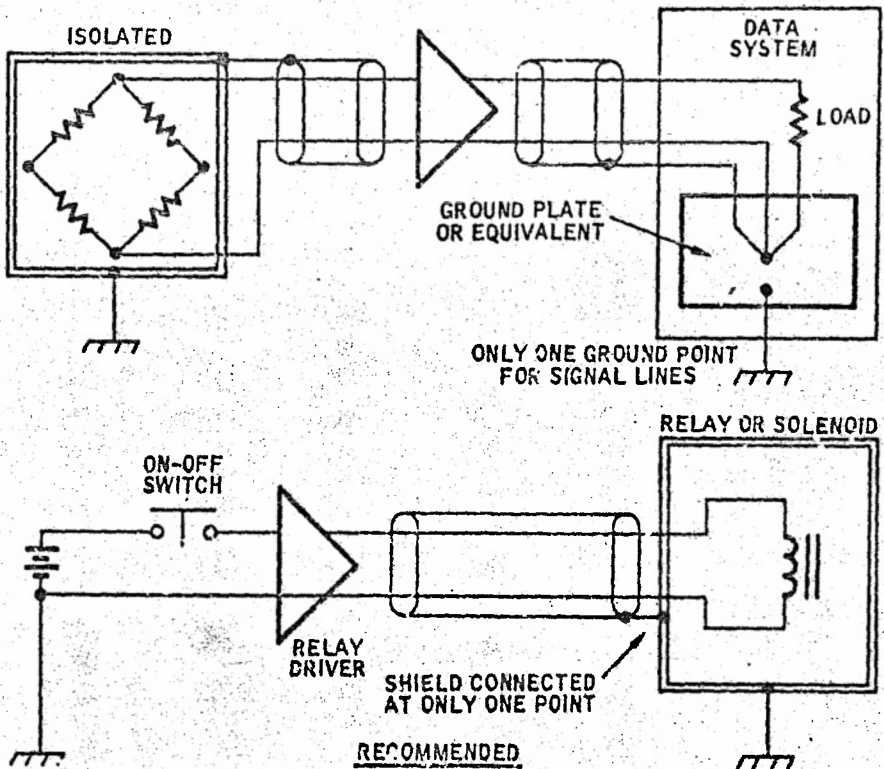

FIGURE 5-15
Correct Technique for Shield Connections to Prevent Ground Loop

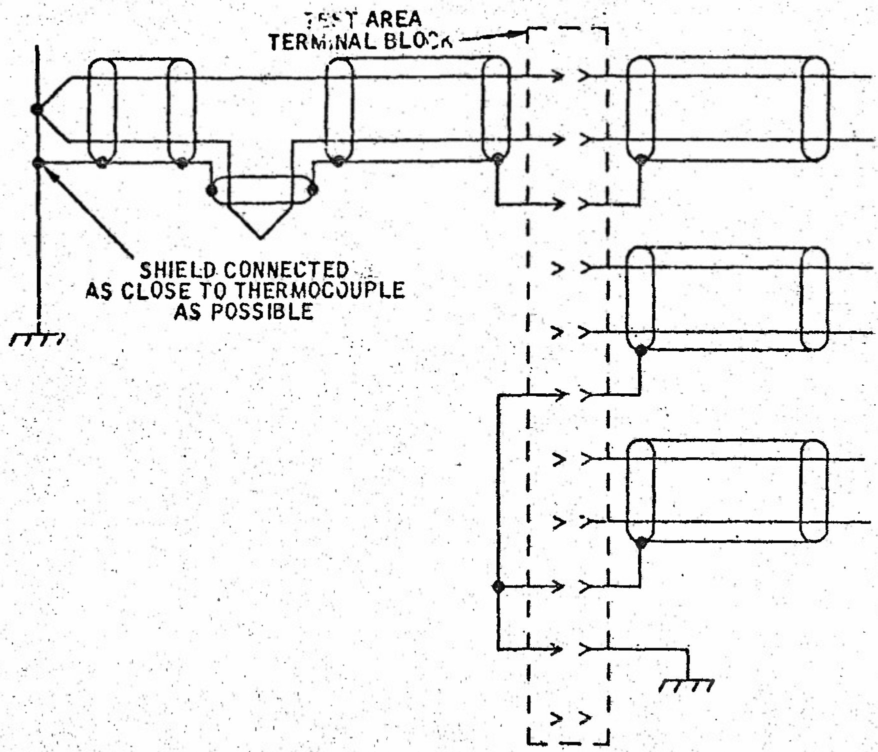

FIGURE 5-16
Shield Connected to Ground as Close to Thermocouple as Possible

made from the earth surface. In addition, since a more stable soil resistivity is found 15 to 20 feet below the earth surface, the ground rod can easily be driven well beyond this depth to obtain a stable earth connection.

Because of the sandy earth conditions of a desert based rocket test facility, a ground rod installation is recommended and the use of proper installation equipment will enable grounds to be driven to depths in excess of 100 feet.

5.5.1 ROD INSTALLATION

The classic sledge hammer is an effective tool for driving ground rods to depths of 8 to 10 feet. However, this method is time consuming and in poor soil conditions would be totally useless. An improved method of driving ground rods is the use of modified sledge hammer approach called the "Chuck and Anvil" method.

Figure 5-19 illustrates the essential components for this method of ground rod installation. This device consists of a chuck and a sliding hammer. It has an advantage over the sledge hammer in that the work may be carried on at a level convenient to the workmen without a ladder or platform and the blow is delivered near the ground level.

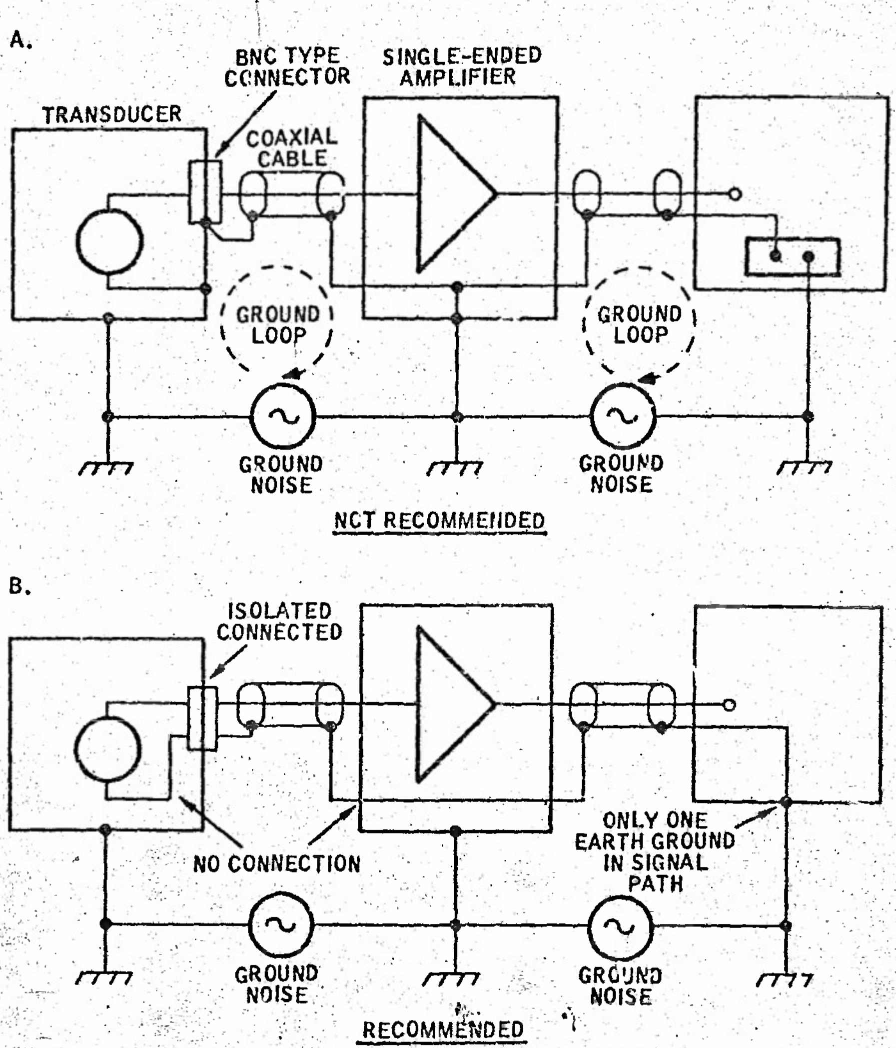

FIGURE 5-17
A. Ground Loop Formed by Shield and BNC Type Connection
B. Elimination of Ground Loop by Isolation of Shield Connection From Chassis and Case Grounds

When ground rods are being driven to considerable depths it is recommended that jointed rods be used. Figure 5-20 illustrates this rod and shows the removeable stud which will take the driving blows. These rods lend themselves very readily to installation by use of an electric hammer or air hammer systems which greatly increase the speed and depth capabilities of driven ground rods.

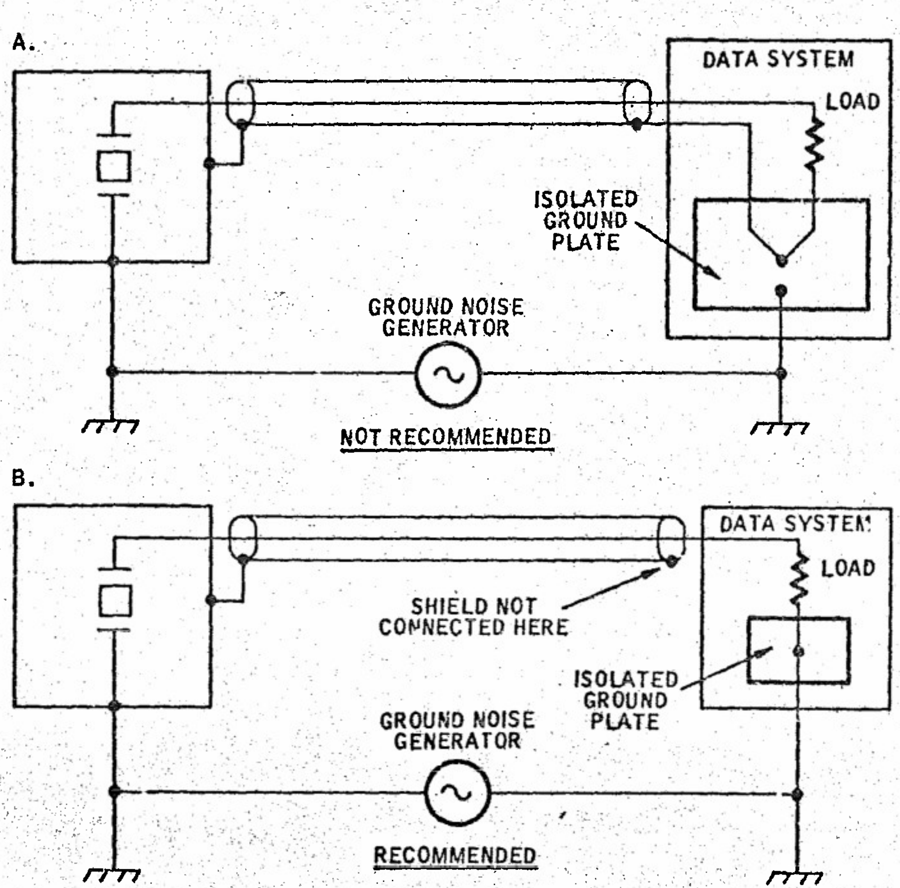

FIGURE 5-18
A. Ground Loop Between Transducer and Data System
B. Ground Loop Open-Circuited at Data System

The electric and air hammers require bulky equipment such as power generators and air compressors. A more convenient hammer is run on gasoline and is self contained. These hammers offer portability and convenience not available in other ground rod installation equipment.

NOTE

A ground rod depth of 20 feet minimum is recommended for a desert test facility installati . It will often be necessary to drive the rods e\ :n deeper to obtain an adequately low grou:d rod to earth resistance.

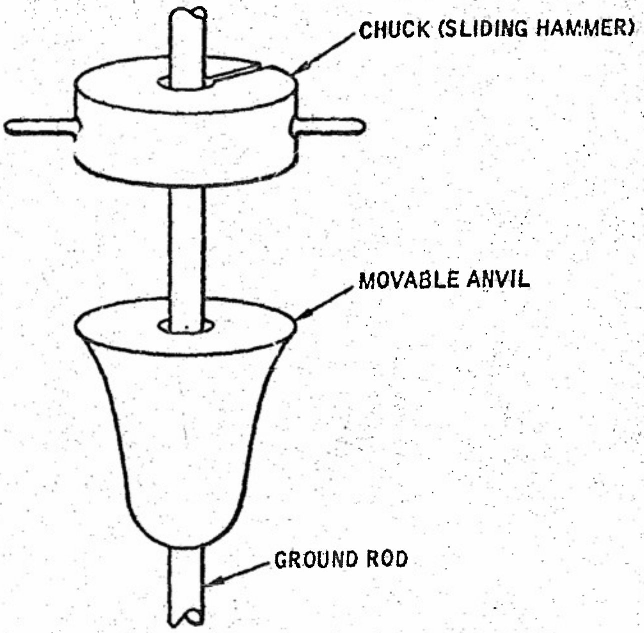

FIGURE 5-19
Chuck and Anvil Method of Ground Rod Installation

5.5.1.1 Soil Treatment to Lower Resistance

Common salt and magnesium sulphate water solutions are chemicals which can be added to the soil to lower the contact resistance of the rod and earth. Chemical treatment can reduce soil resistance up to 90%. Treatment of sandy soil provides the highest degree of improvement and is recommended in a desert test instrumentation facility. Since chemicals will be carried away with the water, frequent maintenance is required to insure a constant low resistance ground rod installation.

A typical method of installing the soil treatment solution is to form a circular trench around the ground rod as shown in Figure 5-21.

A more effective method of soil treatment is shown in Figure 5-22. Here the ground rod is installed inside a tile pipe with a removable cover. This allows ease of inspection and maintenance. The chemical can be added either dry or in a water solution. If added dry, holes in the cover will allow rain or frequent hosing of test area to carry the chemical into the soil if the rod is located outside of the facility. An actual rod installation is shown in Figure 5-23, using this method.

5.5.2 MEASUREMENT OF GROUND RESISTANCE

In areas such as a desert rocket test facility where chemical treatment of the soil is necessary to maintain a low resistance earth connection for the safety of personnel, it is also necessary to monitor the status of this resistance because the

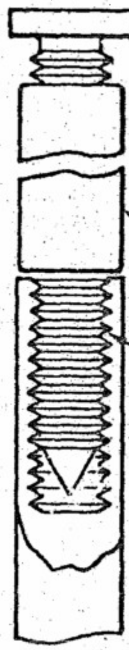

FIGURE 5-20
Joined Ground Rods for Deep Driven Rod Installations

chemicals will deteriorate with climate and soil moisture conditions causing the rod to earth resistance to increase.

There are three basic methods of measuring the resistance of ground rod to earth resistance:

a. Three-point method
b. Fall-of-potential method
c. Ratio method

The resistance of the rod installation should be measured at the time of installation and should be checked every two months after the installation for one year and twice yearly thereafter.

The most convenient method to use is the fall-of-potential method. With the use of a small hand generator set (called a Megger) a known current is passed through the ground rod being tested and one of the two auxiliary earth electrodes. The potential drop between the ground rod and the other auxiliary earth electrode is measured and the ratio of this potential drop to the known current indicates the resistance to ground of the ground rod. The diagram for this test showing an AC current supply is illustrated in Figure 5-24.

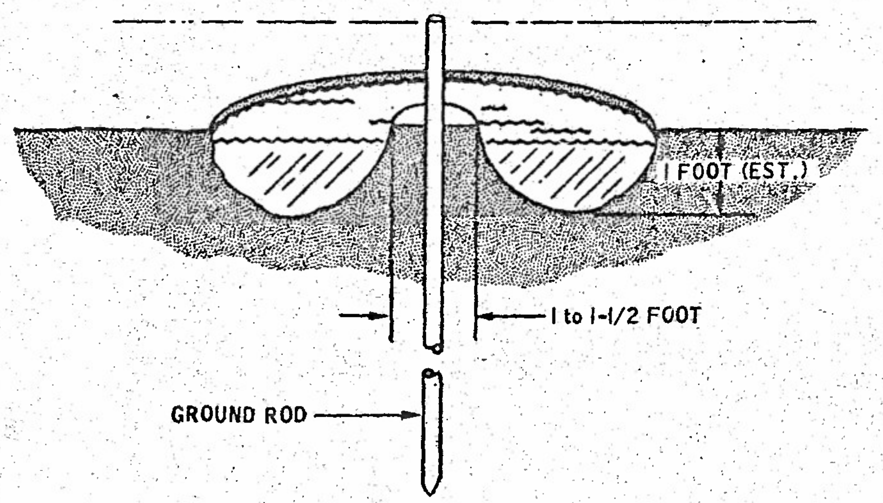

FIGURE 5-21
Trench for Chemical Treatment of Soil

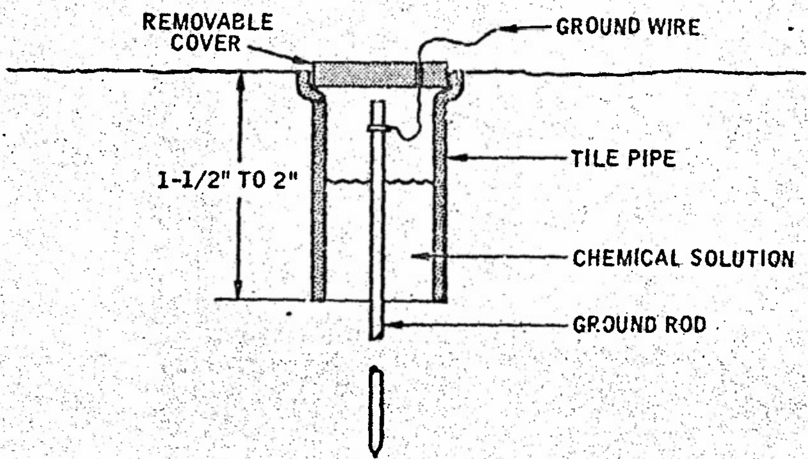

FIGURE 5-22
Ground Rod Installed Inside Tile Pipe

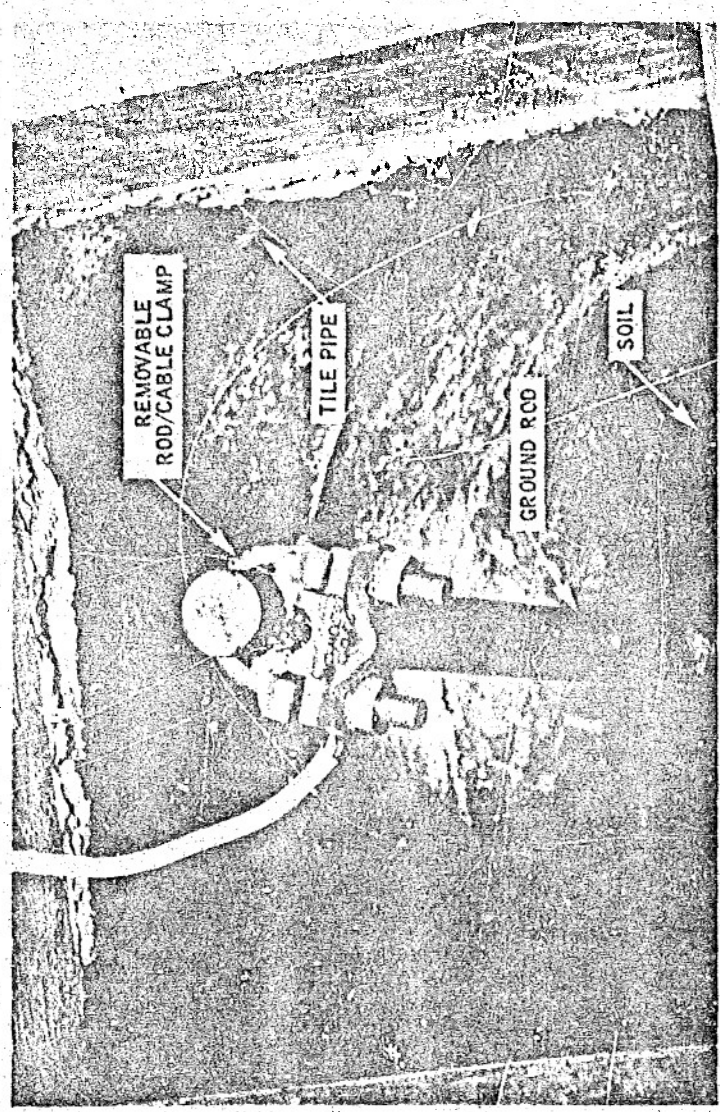

FIGURE 5-23
Actual Ground Rod Installation Using Tile Pipe

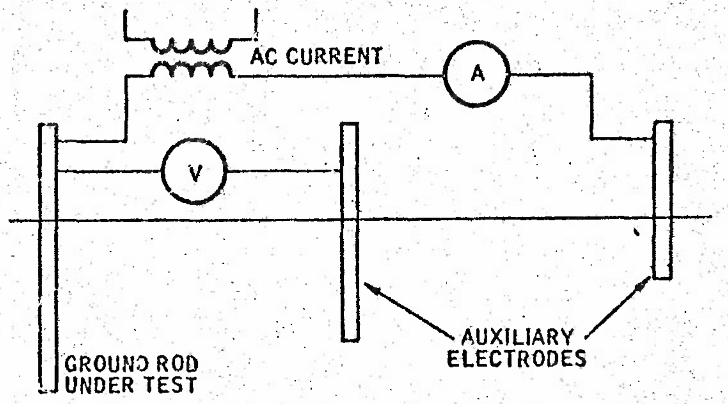

FIGURE 5-24
Fall-of-Potential Method of Ground Rod to
Earth Resistance Measurement

The following procedure outlines the steps required in making a resistance test using the Megger instrument. For more specific information concerning this instrument, contact the James G. Biddle Co., 12092 Foster Road, Los Alamitos, California.

Referring to Figure 5-25 perform the following procedures:

a. Drive two reference or auxiliary electrodes in a straight line with the ground rod being tested.

b. Connect the wires to the rods according to the instructions given for the instrument or as shown in Figure 5-25.

c. The rods are kept in this position for each particular location.

d. The rod spacing is as follows:

1. Rod P_2 is 60 feet from test rod
2. Rod C_2 is 100 feet from test rod

The various methods and equipment available to measure the soil resistivity and ground rod to earth resistance is well documented in available literature.[20, 21]

5.6 MAINTENANCE OF EARTH GROUND CONNECTION

Maintenance of the earth connection requires periodic inspections of the system to assure that the resistance of the earth connection does not increase with time and exceed intended design limits. Changes in resistance can occur due to corrosion of connections, loosening of connections, and changes in soil resistivity.

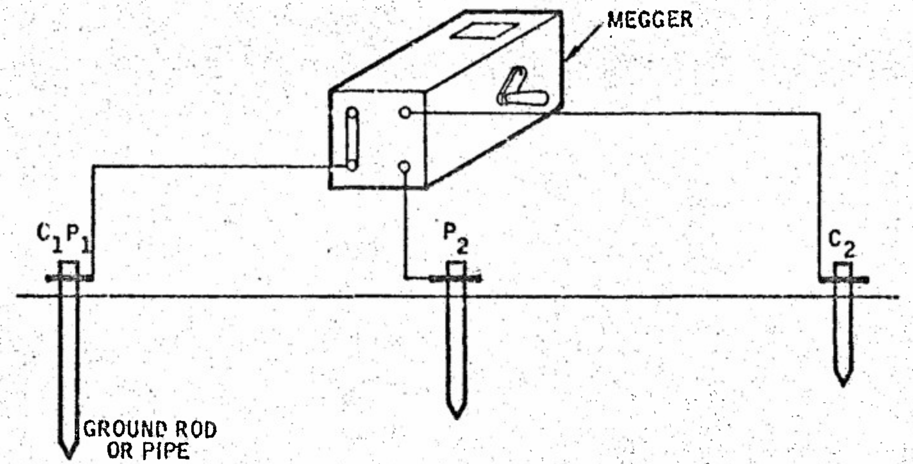

FIGURE 5-25
Ground Rod to Earth Resistance Test

Soil resistivity, in turn, may vary seasonally, or due to a falling water table, or because of depletion of chemicals which were added during installation to lower soil resistivity. Periodic checks are the only means of monitoring the resistance of the earth connection.

NOTE

Periodic inspections should be made every two months for the first year following installation to record seasonal variations. Thereafter, inspections should be made twice a year. Checks should include the following:

a. A visual inspection of all connections. Connections should be inspected for both tightness and corrosion.

b. Ground-resistance measurements should be made. This is especially important where chemicals are used to lower soil resistivity because chemicals are depleted with time and must be replaced periodically.

An increase in resistance which exceeds design limits and cannot be corrected by clearing and tightening connections will require expansion of the earth ground connection system. Installation of additional ground electrodes and/or chemical treatment will probably be required.

5.7 ROUTING OF SIGNAL CABLES AND POWER CABLES

When two signal lines are placed close together which have large voltage or current differences the signal line with the smallest signal will be influenced by the

other line because of the capacitive coupling between them. Also, if one line is carrying large amounts of current which is varied, as in a 60 cycle power line, a magnetic field is produced around the power line which will be coupled into the adjacent wire as shown in Figure 5-26.

Because of these two factors it is necessary that proper routing of all cables be considered in order that noise will be kept at a minimum.

Wiring can be categorized into five basic divisions with respect to signal and relative power levels.

a. Low frequency, low voltage instrumentation lines.

b. DC control lines, with DC level switches and noise producing solenoids and relays.

c. Digital wiring with high frequency switching pulses.

d. High frequency video, such as closed circuit TV and telemetry.

e. AC power wiring.

The wiring as categorized above should be carefully identified and kept isolated from each other as much as possible.

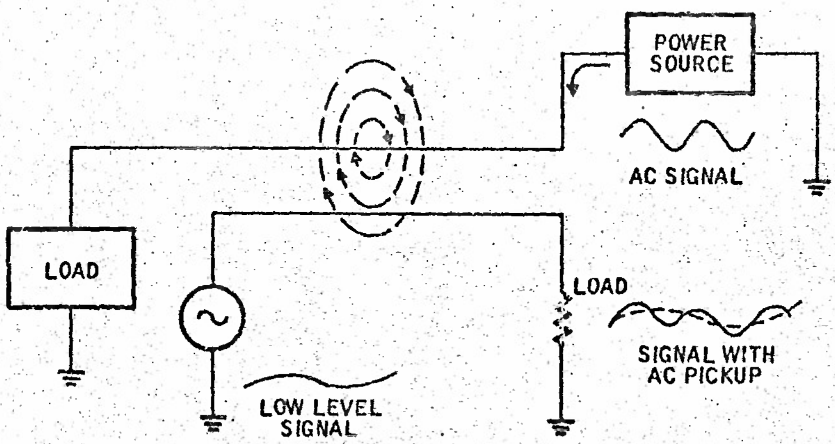

FIGURE 5-26
Magnetic Coupling of High Level Signal Into Low Level Signal Circuit

Category A

a. Wiring in category (A) originating at the test stand should be routed to the data instrumentation system by conduit or cable trays which do not contain any wiring in the other categories.
b. When this wiring is carried into the data system area it should be broken out into an area which is as close to the input devices as possible.
c. Wiring in the other categories should not be allowed to come within three feet of this wiring, if possible.
d. The AC power circuits and low level signals usually must be routed in the same equipment rack. Under this condition all wiring in category (A) should be routed in the upper extremities of the cabinet while the wiring in category (E) be routed in the lower extremities of the cabinets.
e. The crossing of these to wiring categories should be kept to a minimum. One example of how this can be accomplished is illustrated in Figure 5-27.

Category B

Category (B) will not be effected greatly by the wiring of category (E). Therefore, the routing of control wiring can be such that these two categories can, if necessary, share common conduit or cable trays.

Category C

a. Digital wiring in category (C) is a very good noise generator and must be kept confined to the digital system as much as possible.
b. If instrumentation cables are routed into an area with digital wiring all instrumentation cable wiring must be twisted, shielded, and routed in such a way as to provide a maximum separation of the two types of wiring.

Category D

a. Video signals from telemetry and closed circuit TV are becoming more common in a rocket test facility.
b. If carried in conduit or cable trays the cables should be placed in a manner which gives maximum separation of category (A) and (D).
c. The other wiring categories are not particularly sensitive to this type of signal and the routing of this wiring is not too critical.

Category E

a. AC power cables and power distribution wires which are routed into data instrumentation cabinets must be twisted in order to reduce the radiation of 60 cycle fields into sensitive low level circuits.
b. AC power should be routed in metallic conduit inside the cabinets so that the conduit will serve as a shield over the power wires.
c. When conduit is used in this way, care must be exercised to insure that the equipment ground isolation is maintained.

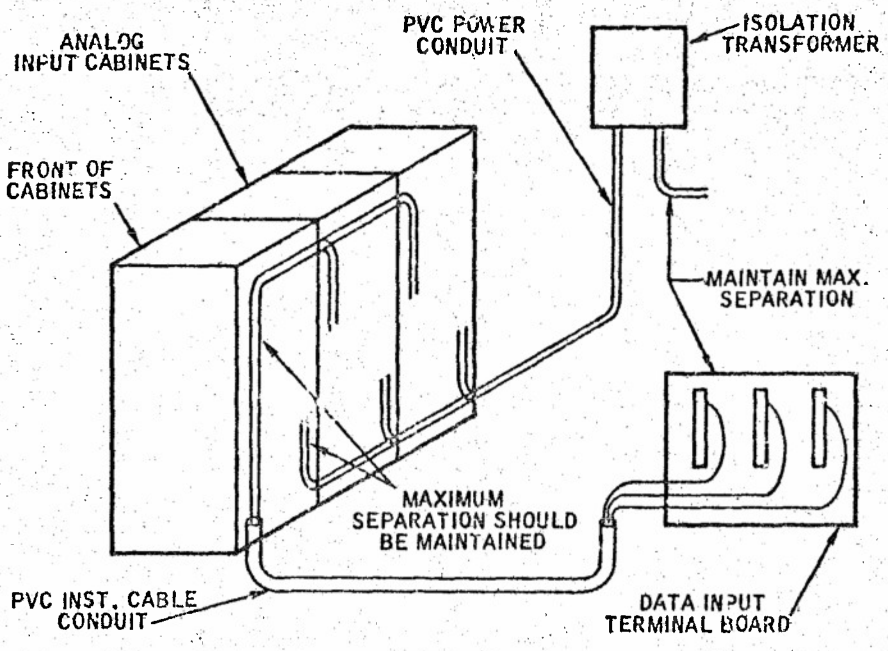

FIGURE 5-27
Distribution of Instrumentation Wiring and
Power Wiring in Equipment Cabinet

5.8 LOW RESISTANCE CONTACT

In a rocket test facility the frequent contamination of the air surrounding the test stand and inside a test chamber causes corrosive action which can lower the accuracy of instrumentation systems. In addition to the corrosive action of the rocket fuels, temperature cycling may produce condensation on metallic surfaces such as cable connector contacts, terminal boards, ground wire bonding points, and signal wire conduit. The useful life of these contacts under such environmental influences will depend upon the proper choice of contact materials and finishes applied to combat corrosion.

Corrosion on the contact pins of a cable connector, on the mating surfaces of terminal board contacts, etc., can add several ohms of resistance in the signal wire.

Because this resistance is not necessarily constant and may vary with environmental changes, an error can result that cannot be compensated by calibration routines.

Dissimilar metals, widely separated in the galvanic series (see Section 2, Table 2-2) should not be volted, riveted, etc., without separation by insulating material at the facing surfaces. In many circuit applications where dissimiliar metals are

required to make electrical contact with each other, the two surfaces must be protected with compatible metal plating, e.g., electroplating, hot dipping, galvanizing, etc.

In all low level instrumentation circuits it is highly recommended that a thickness of 0.000015 inch to 0.000020 inch electroplating of hard, bright gold be used on the contacts to greatly improve resistance to tarnish oxidation and attack by most chemicals. This gold plating will also lower the electrical resistance.

In an existing facility where higher accuracies are desired, all signal lines being used must be checked for corrosion and all contacts in the vicinity of the test area which will be subjected to temperature cycling and corrosive action of fuels and chemicals be cleaned and inspected thoroughly prior to the data run.

Where cable connectors are used to interface between test area or test chamber and the data equipment, these connectors should be protected from the corrosive environment by enclosing the cable connectors in a hermetic type enclosure on the side to be subjected to the corrosive environment.

In order to illustrate how a 10 ohm series corrosion resistance in a low level instrumentation signal wire can contribute error in a measurement, consider a signal current of 1 MA, a voltage of 10 UV will result across this resistance. If a high speed digital data acquisition system with an accuracy of 0.1% and a full scale input signal of 10 MV from the transducer, the digital system is able to sense a signal change of 10 UV. Thus, the resistance contributed by poor electrical contact and corrosion can add significant error to the data which will be detected by the data system.

APPENDIX A

Earth Resistivity

Assume a metallic sphere of radius A, surface area = $4\pi A^2$ which is shown in Figure A-1, thus for this analysis half the sphere will be considered.

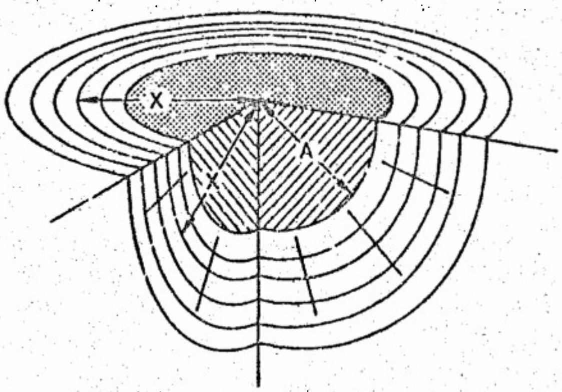

FIGURE A-1
Metallic Hemisphere Burned Into Earth With Radius A. (From J. R. Eaton, "Grounding Electric Circuits Effectively," G. E. Review, June 1941)

The resistance offered to a flow of current from the sphere will be that soil immediately surrounding and in contact with the hemisphere.

Given:

Resistance of a conductor of uniform cross-section is

$$R = \rho \frac{l}{A}$$

where

ρ = specific resistivity of the conductor, ohm-inches
l = length, inches
A = cross-sectional area, inches^2

R can be applied to the hemisphere if the soil is considered the conductor whose area is increasing with distance from the hemisphere, dx. At a given distance from the hemisphere the surface area will be $2 x^2$, thus

$$R = \rho \int_A^\infty \frac{dx}{2\pi x^2} = \frac{\rho}{2\pi A}$$

The above equation states that the soil resistance offered to the hemisphere is directly proportional to the earth resistivity surrounding the hemisphere and is inversely proportional to the surface area of the hemisphere or ground electrode.

Table A-1 gives some general data on earth resistivity that considers only the type of soil and not environmental conditions.

SOIL	RESISTANCE (OHMS) 5/8 IN. X 5 FT. RODS			RESISTIVITY (OHMS PER CM^3)		
	Avg.	Min.	Max.	Avg.	Min.	Max.
Fills						
Ashes, cinders, brine waste	14	3.5	41	2,370	590	7,000
Clay, shale, gumbo, loam	24	2	98	4,060	340	16,300
Same-with varying proportion of sand and gravel	93	6	800	15,800	1,020	135,000
Gravel, sand, stones, with little clay or loam	554	35	2,700	94,000	59,000	458,000

[1] Bureau of Standards, Technical Report No. 108.

TABLE A-1
The Resistivity of Different Soils[1]

The resistivity of soil varies at different depths below the surface because of three variables.

a. Moisture

b. Temperature

c. Soil composition

Variations of soil resistivity with moisture are very important since a very good low-impedance ground connection might become, due to fluctuations of the moisture content of the soil, a very high resistance ground that would effectively compromise the ground system. (See Table A-2). For this reason ground rod installations should be periodically inspected and monitored to insure the quality of the grounding system.

MOISTURE CONTENT (PERCENT BY WEIGHT)	RESISTIVITY (OHMS PER CM CUBE)	
	TOP SOIL	SANDY LOAM
0	> 1,000 X 10^6	> 1,000 X 10^6
2.5	250,000	150,000
5	165,000	43,000
10	53,000	18,500
15	19,000	10,500
20	12,000	6,300
30	6,400	4,200

[1] P. J. Higgins, "An Investigation of Earthing Resistances," IEE Journal, Vol. 68, p. 136

TABLE A-2
The Effect of Moisture Content on the Resistivity of Soil[1]

Another important environmental factor that influences soil resistivity is ambient temperature. For wide variations in temperature, the resistivity of the soil has shown wide variations in value. The effect of temperature on the resistivity of soil is listed in Table A-3.

SANDY LOAM: 15.2% MOISTURE		
TEMPERATURE		RESISTIVITY
°C	°F	(Ohms/cm^3)
20	68	7,200
10	50	9,900
0 (water)	32	13,800
0 (ice)		30,000
- 5	23	79,000
-15	14	330,000

TABLE A-3
The Effect of Temperature on The Resistivity of Soil

If temperatures vary between 20°F and 100°F in a particular locality, according to the season, it is usually found that, approximately three feet below the surface, the swing is not nearly as wide.

The resistivity of the soil varies at different depths below the surface because of the composition of soil in the various layers, and the physical position of the soil within the layers. Figure A-2 shows this variation of resistivity with depth. The conductance (reciprocal of resistance) is plotted to show a more meaningful relationship at the point at the lower end of the ground rod. It will be noted from these curves that the sharp increase in conductance, after 30 feet, is due to ambient climatic conditions no longer affecting this parameter in any way.

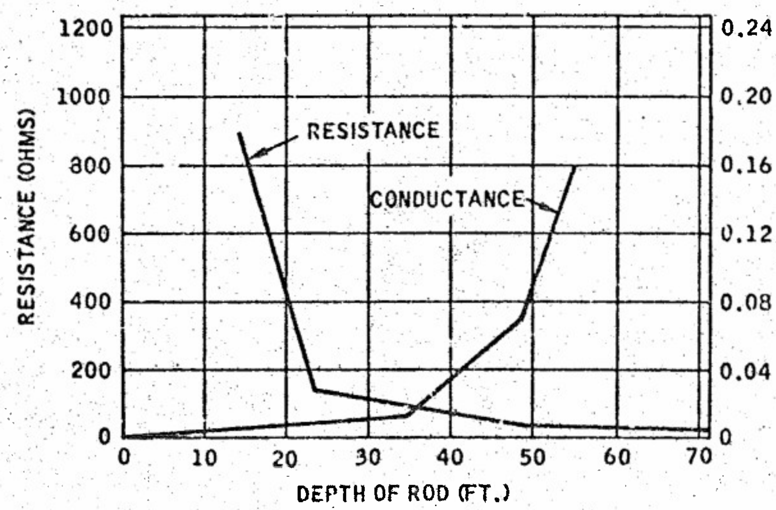

FIGURE A-2
Resistance and Conductance Curves As a Function of Rod Depth

Since it has been established that areas of high resistivity exist in which ground rods must be driven for a particular installation, it will be shown that in certain situations it is practical to treat the soil around the ground rods so that ground resistivity may be reduced. This treatment merely consists of mixing the soil around the ground rods with fine common salt (sodium chloride) before the soil is compacted into place. Data are available that show that for sandy loam with a moisture content of 15 percent by weight, and an ambient temperature of 40°F, the addition of salt to the value of 0.1 percent of the weight of the moisture reduces the resistivity by a factor of 10, and the addition of salt to the value of 20 percent of the weight of the moisture reduces the resistivity by a factor of 100.

When salt is used to treat the soil around electrodes, it must be remembered that salt will be dissolved away. Figure A-3 shows how the resistance varies as the salt content reduces over an interval of time. Resalting reduces the resistance again. Salting, to obtain a low ground resistance, therefore, requires periodic maintenance to assure that a low ground resistance is being kept.

The formula for the approximate resistance to the flow of current away from a rod or pipe, driven vertically into the earth is as follows:

$$R = \frac{100\,\rho \log \frac{41}{D}}{2\pi l} \quad \text{(in ohms)}$$

where

ρ = the resistivity of the surrounding soil in meter-ohms

l = the length of the ground rod in centimeters

D = is the diameter of the ground rod in centimeters

Figure A-4 shows, graphically, the approximate results of the above equation.

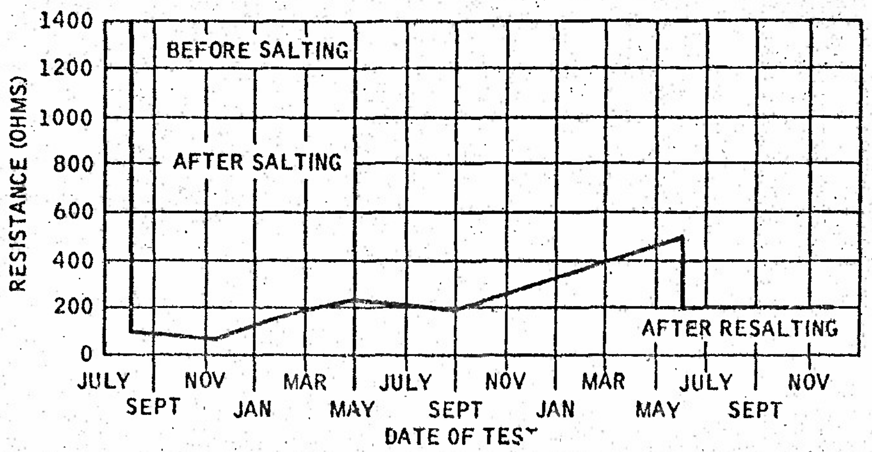

FIGURE A-3
Changes In Resistance of a Ground Connection
in Response to Presence of Salt Over a Considerable Period

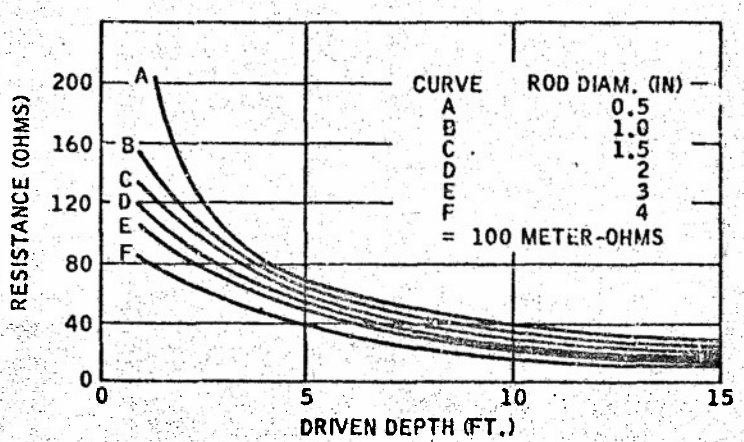

FIGURE A-4
Theoretical Variation of Resistance
with Depth for Round Electrodes of Various Diameters

APPENDIX B

Cable Characteristics and Formulas

These formulas and characteristics are useful for resistance and impedance calculations for electrical conductors and coaxial cable.

Length and Weight

Weight (lb./1000 ft.)

$$= d^2 \times \delta \times 0.34049 \times 10^{-3}$$

Length (ft./lb.)

$$= \frac{1}{d^2} \times \frac{1}{\delta} \times 2.9369 \times 10^6$$

d = diameter of wire, mils

δ = density of the wire material

Total Resistance

$$R = \frac{K \times l}{CM}$$

R = resistance, ohms,

l = length of wire, ft.,

CM = circular mil area,

K = resistance of one mil-ft., ohms

Density

$$\delta = \frac{W_a \times d}{W_a - W_1}$$

δ = density, grams/cc.

W_a = weight in air, grams

W_1 = weight in liquid, grams

d = density, grams/cc.

Temperature Correction

$$R_1 = R_0 \left[1 + \alpha (t - t_0)\right]$$

R_1 = resistance at operating temperature

R_0 = resistance at a known temperature

t = operating temperature

t_0 = temperature for a known resistance

α = temperature coefficient of resistance at t_0 (0.00393/degree C at 20^0 C.).

Areas

Area, circular mils = d^2

Area, square mils = Thickness X Width (in mils)

Convert circular mils to square mils: d^2 X 0.7854

Convert square mils to circular mils: Sq. Mils X 1.2732

Transmission Line Characteristic Impedance (Z_0):

Single Coax Line

$$Z_0 = \frac{138}{\sqrt{\epsilon}} \log_{10} \frac{D}{d}$$

ϵ = dielectric constant,

D = inner diameter of outer conductor,

d = outer diameter of inner conductor.

Balanced Shielded Line

$$Z_0 = \frac{276}{\sqrt{\epsilon}} \log_{10} \left[2v \frac{1 - \delta^2}{1 + \delta^2} \right]$$

$$= \frac{120}{\sqrt{\epsilon}} \ln \left[2v \frac{1 - \delta^2}{1 + \delta^2} \right]$$

$$\delta = \frac{h}{D}; \; v = \frac{h}{d}$$

D = inner diameter of outer conductor

d = outer diameter of inner conductor

h = distance between two inner conductor centers

Open Two-Wire Line in Air

$$Z_0 = 120 \cosh^{-1} \frac{D}{d}$$

$$= 276 \log_{10} \frac{2D}{d}$$

$$= 120 \ln \frac{2D}{d}$$

d = outer diameter of conductors

D = distance between conductor centers

Capacitance of Coax Cable

$$C = \frac{7.36\epsilon}{\log_{10} \frac{D}{d}}$$

C = capacitance, $\mu\mu f$/ft.,

ϵ = dielectric constant,

D = inner diameter of outer conductor

d = outer diameter of inner conductor

Attenuation for Copper Coax Line

$$R_t = 0.1 \left(\frac{1}{d} + \frac{1}{D}\right) \sqrt{f}$$

$$A = 4.35 \frac{R_t}{R_0} + 2.78 \sqrt{\epsilon}\ (pf)\ f$$

R_t = total line resistance in ohms per 100 ft.
R_0 = characteristic impedance of coax
D = inner diameter of outer conducter in inches
d = outer diameter of inner conducter in inches
ϵ = dielectric constant
A = attenuation in db per 100 ft.
(pf) = power factor of dielectric medium
f = frequency in megacycles

APPENDIX C

Common-Mode Equations

The term "common-mode" defines a mode of operation of an electronic device the same as the term "normal-mode." Common-mode for a differential amplifier refers to its response to a common-mode signal as shown in Figure C-1.

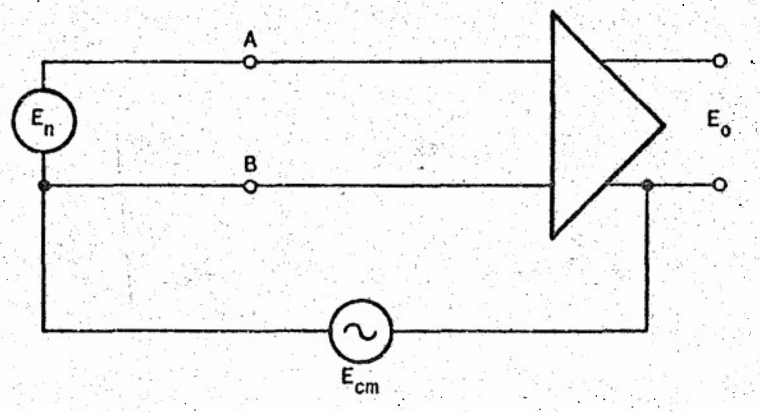

FIGURE C-1

Common-Mode Voltage

E_{cm} is a common voltage to both input terminals A and B. Therefore, E_{cm} is a common-mode voltage. E_n on the other hand is a normal or "normal-mode" voltage and E_n times the amplifier gain K produces output E_o.

A perfect differential device will have no response at its output as a function of a common-mode signal. The ability of a device to reject a common-mode signal is its "common-mode rejection ratio," CMR.

$$\text{CMR} = \frac{E_{cm}}{E_x} \tag{1}$$

E_x is the voltage difference caused between points A and B (see Figure C-1) as the result of applying E_{cm}. A voltage E_x can exist due to leakage paths as illustrated in Figure C-2 by Z_1 and Z_2. These paths occur primarily as the result of capacitance and resistance internal to the amplifier.

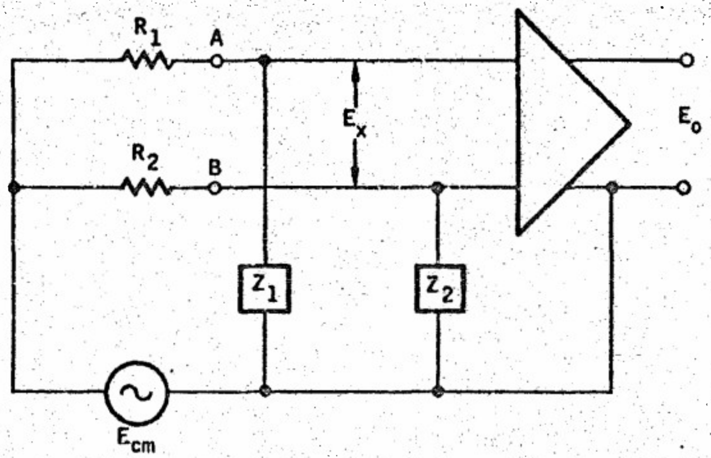

FIGURE C-2
Leakage Impedance

It can be seen that if line resistances R_1 and R_2 exist, as they will, then due to the dividing action R_1, Z_1. and R_2, Z_2, a difference of potential E_x can exist between points A and B due to E_{cm}. E_x acts to the amplifier the same as a normal-mode signal. The amplifier output, due to E_{cm}, is therefore

$$E_o = (E_x)(K) \tag{2}$$

or

$$E_o = \frac{E_{cm}\,(K)}{CMR} \tag{3}$$

The equation used for measuring the common-mode rejection of an amplifier is derived from equation (3):

$$CMR = \frac{E_{cm}\,(K)}{E_o} \tag{4}$$

Note that any differential device can exhibit a CMR. In the event that K = unity then the CMR becomes

$$CMR = \frac{E_{cm}}{E_o} \qquad K=1 \tag{5}$$

This can be used for such devices as commutators and differential switches.

Note also that if $R_2 \approx O$ in Figure C-2, E_x becomes $\frac{E_{cm} R_1}{Z_1 + K_1}$. This means that if $Z_1 \gg R_1$ then

$$E_x \approx E_{cm} \frac{R_1}{Z_1} \quad (6)$$

and $$CMR \approx \frac{Z_1}{R_1} \quad (7)$$

It is interesting to observe the relationships among R_1, Z_1, R_2, and Z_2. To simplify the analogy which follows, Z_1 and Z_2 will be assumed to be capacitive reactances X_{c_1} and X_{c_2} respectively. Figure C-3 illustrates the appropriate sections of the circuit to be considered.

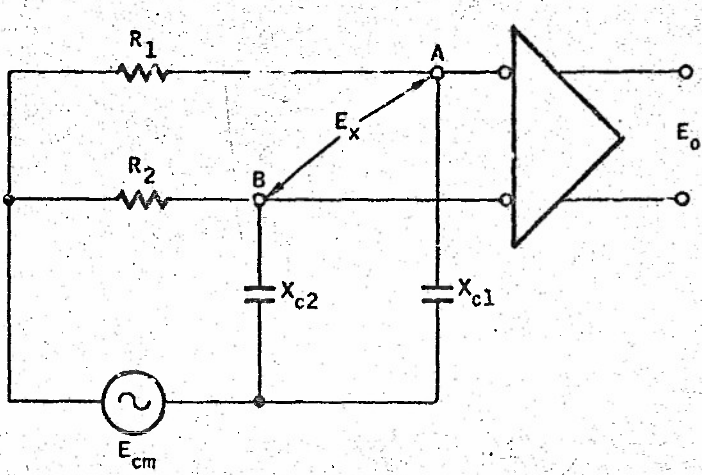

FIGURE C-3
Common-Mode Circuit

A "common-mode circle" may be used to illustrate the dividing function of R_1, X_{c_1}, and R_2 X_{c_2}. This is given in Figure C-4.

An interesting feature of the common-mode circle is that it may graphically demonstrate the three methods by which common-mode error, E_x, can be reduced:

a. Decrease E_{cm} - By decreasing E_{cm}, the other segments of the diagram decrease proportionately. CMR (the ratio of E_{cm} to E_x) will remain constant, however E_x, the error voltage will be reduced.

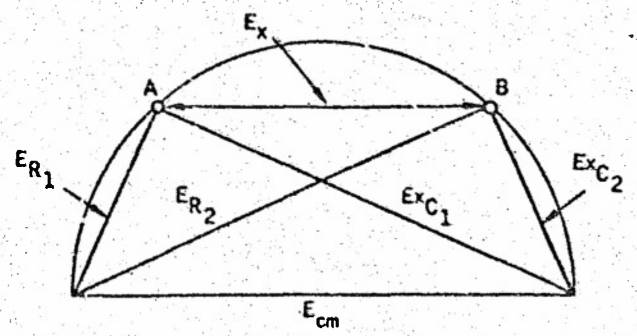

FIGURE C-4
Common-Mode Circle

b. Balance E_{r_1} with E_{r_2} - By manipulation of R_1 and R_2, the error voltage E_x may be reduced to zero. This is mechanically illustrated in Figure C-4 by converging the two points A and B on the circle.

c. Increase X_{c_1}, X_{c_2} - Since $X_c = \frac{1}{2\pi fc}$, it is seen that X_{c_1} and X_{c_2} can be increased by decreasing each of the two capacitances. If both X_c's are increased sufficiently then the two points A and B will move to the extreme left of the circle causing E_{r_1} and E_{r_2} to diminish to negligible values. E_x therefore diminishes. This technique for decreasing E_x is that which is accomplished by high CMR within an isolated differential amplifier and optimum shielding of the input signal lines.

APPENDIX D

Digital System Accuracy

There are several methods by which the accuracy of A/D Data Acquisition Systems can be determined. The method used should be practical yet comprehensive and rigorous. If the only system output method available is a digital display, then the accuracy measurement should be based on this device. A most comprehensive technique is computer analysis. This is also extremely rigorous and practical if a method for transferring the digital data into a computer is readily available.

The information given below applies primarily to computer analysis for system accuracy determinations. However, abbreviations of the methods can be used where system readout devices are limiting.

<u>Precision Error e_p</u>

System precision is perhaps the most significant factor relating to performance quality. Precision is commonly measured in terms of precision error, e_p, which is the three-sigma (3σ) deviation from the mean count value in percent of full scale.

Three sigma is best described by reference to Figure D-1.

The graph of Figure D-1 describes a gaussian or random distribution of count values about the mean count value $\bar{x}$. $\bar{x}$ is calculated by taking n data samples and then averaging them. n should be large enough so that by increasing n, no appreciable change is noted in $\bar{x}$.

In Figure D-1, $\bar{x}$ is shown to have the highest frequency of occurrence while count values above and below $\bar{x}$ occur less frequently.

Three-sigma is a measure of the deviation of count values from the mean count value $\bar{x}$. 3σ is statistically determined by applying the following formula

$$3\sigma = 3\sqrt{\frac{\sum_{N=1}^{n} (x_i - \bar{x})^2}{n-1}}$$

where

x_i = individual sample count values

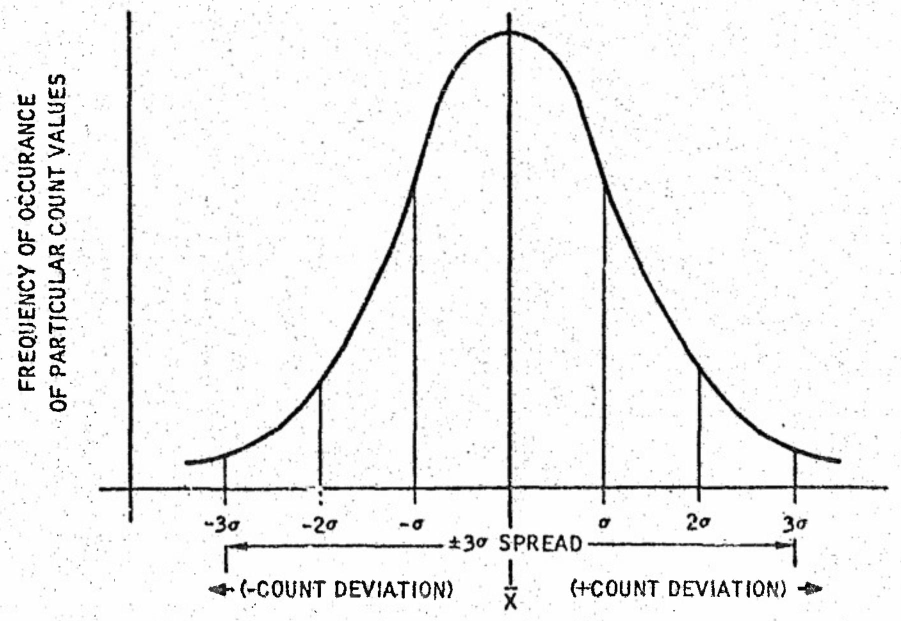

FIGURE D-1

Frequency Distribution of Count Values - Gaussian Curve

By definition, the $\pm 3\sigma$ deviation includes 99.73% of the n samples taken to calculate $\overline{x}$. Those samples beyond the $\pm 3\sigma$ limits are shown at the outer edges of the bell shaped curve of Figure D-1.

e_p is defined as:

$$e_p = \frac{\pm 3\sigma}{x_F} \times 100$$

where

x_F = Full scale count value of system

e_p can be measured for a single channel or for all channels of a digital system. The measurement usually consists of connecting a precision voltage source in the zero to full scale range at the channel input and making a digital tape recording of the resulting data. The tape is then taken to a computer facility for

processing. The computer output will ordinarily be a line printer with e_p listings for all channels and input voltages which are included in the system accuracy test.

A sample calculation of e_p is given in Table D-1.

Count Value x_i	Number Of Times x_i Occurs (f)	$\left(\frac{\sum x_i}{n}\right) = \bar{x}$	$x_i - \bar{x}$	$(x_i - \bar{x})^2$	$f\,(x_i - \bar{x})^2$
+6479	4	6482	-3	9	36
+6480	89	6482	-2	4	356
+6481	687	6482	-1	1	687
+6482	8455	6482	0	0	0
+6483	670	6482	1	1	670
+6484	90	6482	2	4	360
+6485	5	6482	3	9	45
$n = 10,000$		6481.999		$\sum_{N=1}^{n} (x_i - \bar{x})^2 =$	2154

TABLE D-I

$$3\sigma = 3\sqrt{\frac{\sum_{N=1}^{n} (x_i - x)^2}{n - 1}}$$

If $x_F = 10,000$

$$3\sigma = 3\sqrt{\frac{2,154}{9,999}}$$

$$3\sigma = 2.046$$

$$e_p = \frac{\pm 3\sigma}{x_f} \times 100$$

$$e_p = \frac{2.046}{10,000} \times 100$$

$$e_p = \pm .02046\%$$

Linearity Error e_L

Linearity is measured in terms of deviation from linearity (linearity error). A generally accepted method of measurement is to establish a straight line by

taking two $\overline{x}$ points, one at 0% full scale input and the other at 90% full scale input. This should be done once for each polarity in a bi-polar system. Figure D-2 describes the method and shows how the resulting e_L is obtained.

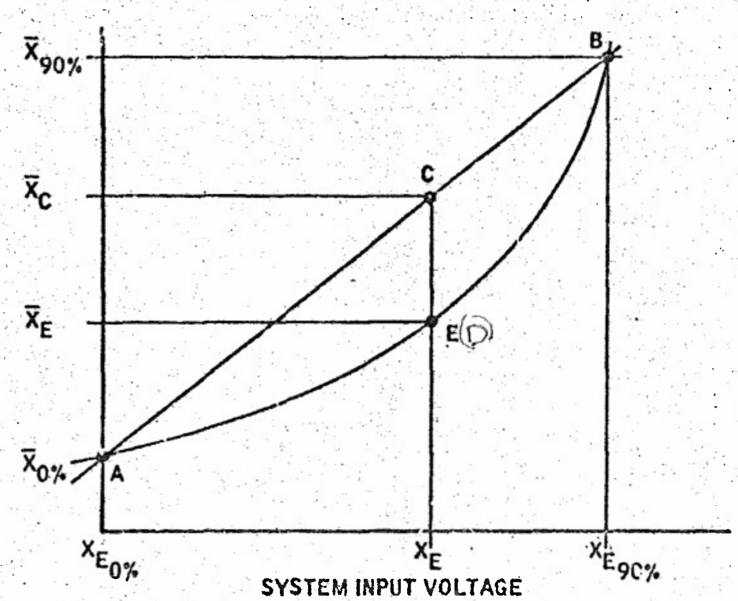

FIGURE D-2

Output Average Count $\overline{x}$, vs. Input Voltage x_E

Once the two points A and B are established, a theoretical point C may be found for any theoretical x_E. When x_E is applied and point D actually results, an error is indicated which is a function of the difference between points C and E. The corresponding $\overline{x}$ values $\overline{x}_C$ and x_E are used to give the error value.

$$e_L = \frac{|\overline{x}_C - \overline{x}_E|}{x_F} \times 100$$

$\overline{x}_E$ is the actual $\overline{x}$ resulting from input x_E.

$\overline{x}_C$ is calculated by

$$\overline{x}_C = \frac{\overline{x}_O + x_E (\overline{x}_{90\%} - \overline{x}_{0\%})}{x_{E90\%}}$$

In a computer analysis it is usually sufficient to take 10 x_E points for the linearity determination. These can be +0%, +90%, +70%, +50%, +20%, -0%, -90%, -70%, -50%, and -20%.

A sample calculation of linearity error e_L is given below:

Given

$$\bar{x}_{90\%} = +8200$$

$$\bar{x}_{0\%} = +0100$$

$$\bar{x}_E = +4895$$

$$\bar{x}_C = +4503$$

$$\bar{x}_F = 10,000$$

then

$$\bar{x}_C = 0100 + 4895 \left(\frac{8200 - 100}{9.000}\right) = 4505$$

$$e_L = \frac{+4505 - 4503}{10,000} \times 100$$

$$e_L = 0.02\%$$

The system e_L is the maximum e_L found for any x_E input.

Common-Mode Rejection CMR

Many digital systems have single-ended inputs and therefore are not subject to CMR tests. If differential inputs are used, a difference in precision errors may be used as an approximation to determine CMR. If $3_{\sigma_{CMR}}$ = $\pm 3_\sigma$ count error with common-mode voltage applied and 3_σ = $\pm 3_\sigma$ count error without common-mode voltage applied then

$$CMR = \frac{(CMV)\,(x_F)}{(3_{\sigma_{CMR}} - 3_\sigma)\; E_F}$$

where

CMR = peak common-mode voltage applied

x_F = Full scale digital count

E_F = Full scale voltage input

EXAMPLE

Given:

$3\sigma_{CMR}$ = 30 counts

3σ = 20 counts

CMV = 10 volts peak

x_F = 10,000 counts

E_F = 5 millivolts

then

$$CMR = \frac{10\ (10,000)}{(40\ -\ 20)\ (5\ \times\ 10^{-3})} = 1,000,000$$

Note that both common-mode rejection and channel-to-channel common-mode rejection can be approximated by the above expression depending on test set-up. Note also, that since $3\sigma_{CMR}$ is obtained using a sinusoidal error contributor CMR, precaution must be taken to insure that a sufficient number of samples n are taken to stabilize $3\sigma_{CMR}$.

Theoretical Error Analysis

In order to specify the accuracy of a digital A/D system before it is manufactured, it is necessary to make a theoretical error analysis.

Precision error e_p is a combination of all gaussian type errors contributed by components of the system. e_p is determined as follows:

$$e_p = \sqrt{e_n^2 + e_s^2 + e_d^2 + e_c^2 + e_x^2 + e_m^2}$$

Each contributing error e_i is in itself a maximum error taken as percent of full scale:

e_n = noise error

e_s = combined zero and gain stability error taken at constant temperature and over a specified period of time (1 hr, 8 hrs, 40 hrs, 6 months etc.)

e_d = drift error due to temperature change. This error is calculated by using the component temperature coefficient

e_c = Common-mode error taken at 0 to 60 CPS with a specified line unbalance and peak common-mode voltage (may be omitted from e_p if e_c is to be measured independently)

$$e_c = \frac{(\text{peak common-mode voltage}) \times 100}{(\text{common mode rejection ratio})\ (\text{full scale input voltage})}$$

e_x = cross talk error

e_m = A/D system error due to commutation, sample-and-hold buffer amplifier, A/D converter, etc.

Linearity error e_L is taken directly from specified component non-linearities. e_L is the direct sum of all component non-linearities.

Measured system errors should be equal to or better than those determined by theoretical analysis as given above.

APPENDIX E
Glossary

ACCEPTANCE TEST: A test made to demonstrate the degree of compliance with specified requirements.

ACCURACY: Freedom from error. Accuracy contrasts with precision; e.g., a four-place table correctly computed is accurate; a six-place table containing an error is more precise, but not accurate.

AIRCRAFT WIRE: An electrical wire primarily designed for the extreme conditions (temperature, altitude, solvents, fuels, etc.) of Airborne equipment.

AIR SPACED COAX: A coaxial cable in which iar is basically the dielectric material. The conductor may be centered by means of a spirally wound synthetic filament, beads or braided filaments. This construction is also referred to as an Air Dielectric.

ALLOY: A metal made by the fusion of two or more metals.

ALTERNATING CURRENT (AC): Electric current that reverses its flow in each direction at regular alternate intervals. The frequency of the change in flow is expressed in cycles per second.

ALUMEL: An alloy used for thermocouple and thermocouple extension wire.

AMBIENT TEMPERATURE: The temperature of a surrounding cooling medium, such as gas or liquid, which comes into contact with heated parts of an apparatus.

AMPERE: The unit expressing the rate of flow of an electrical current. One ampere is the current flowing through one ohm resistance with one volt pressure.

AMPLIFIER, BUFFER: An amplifier used to isolate the output of any device; e.g., oscillator, from the effects produced by changes in load from subsequent circuits.

ANALOG-TO-DIGITAL CONVERTER (ADC): An instrument used to convert analog voltages, either low level ($\pm$10MV full scale) or high level ($\pm$ 10V full scale) voltages to digital binary coded values which are proportional to the analog input voltages.

ANC-68: This military specification covers 2 and 3 conductors, 18 AWG through 6 AWG flexible portable type power cord.

ANC-161: This military specification covers low tension, aluminum conductor, insulated, single conductor cable for aircraft use.

ANGLE OF ADVANCE: The angle between a line perpendicular to the axis of the cable and the axis of any one member or strand of the braid.

ANJC-48A: This military specification covers low tension, copper conductor, insulated, single conductor cable for aircraft use.

ANTENNA WIRE: A wire usually of high tensile strength such as Copperweld, Bronze, etc., with or without insulation used as an Antenna for Radio and Electronic equipment.

ARC: Complete breakdown of the gas dielectric between two conducting surfaces or electrodes as a result of ionization of the gas by a high voltage gradient. Evidenced by intense incandescence of the gas.

ARMATURE WIRE: Stranded annealed copper wire, straight lay, soft loose white cotton braid. It is used for low voltage, high current rotor winding motors and generators. Straight lay permits forming in armature slots and compressibility.

ARMORED CABLE: A cable covered with a heavy outer braid of metal or spiral steel tapes for the purpose of mechanical protection.

ASBESTOS: A non-metallic mineral formed in the earth's crust; when fabrized, it is useful as an insulating material on wire because of its resistance to heat and flame, as well as its insulating properties.

ASESA: Armed Services Electro Standards Agency.

ASPHALTED BRAID: A textile braid on wire impregnated with a petroleum derivative much like tar. The application of such a braid affords some degree of weatherproofing.

ASTM - American Society for Testing: An organization that tests materials and attempts to set standards on various materials for Industry.

ATTENUATION: Attenuation is a general term used to denote a decrease in magnitude in transmission from one point to another. It may be expressed as a ratio or, by extension of the term in decibels.

AUDIO CHANNEL WIRE: A small diameter shielded and jacketed wire used primarily in Radio and Television for wiring consoles, panels, etc.

AUTO PRIMARY WIRE: A single or multi-conductor wire used for original equipment or replacement on Automotive Products. Normally low voltage, resistant to oil, acid and weather.

AWG - American Wire Gauge: The standard for copper wire sizes. The diameters of successive sizes vary in geometrical progression.

BALANCED LINE: A transmission line consisting of two conductors in the presence of ground, capable of being operated in such a way that the voltages of the two conductors at all transverse planes are equal in magnitude and opposite in polarity with respect to ground, the currents in the two conductors are equal in magnitude and opposite in direction.

BALANCED LOAD: In the case of a three-phase power system, the loads between each of the three phases are identical. For a single-phase, three-wire system the loads between each "hot" wire and the neutral are identical.

BALCO: Wilbur Driver Company Trade Mark name for a resistance wire; it is used in devices where self-regulation by temperature is required; it is an alloy of 70% nickel and 30% iron.

BALLISTIC MISSILE: A self-powered bullet-shaped weapon capable of carrying an explosive to a distant target. Usually follows a predetermined fixed course. The name is derived from artillery type ballistic projectiles.

B AND S GAUGE: Brown and Sharpe wire gauge where the conductor sizes rise in geometrical progression. Adopted as the American Wire Gauge standard.

BAND PASS: Number of cycles/sec expressing the difference between the limiting frequencies at which the attenuation to a single frequency energy is the desired amount (usually half power or three DB) of the attenuation to single frequency energy at the mid frequency between the two limiting points.

BANDWIDTH: The frequency range or difference between the limiting frequencies of a band.

BARE CONDUCTOR: A conductor not covered with any insulating material.

B.C.: Abbreviation for bare copper.

BEADED COAX: A coaxial cable in which the dielectric consists of beads made of various materials.

BIT (A CONTRACTION OF BINARY DIGIT): A whole number in the binary scale of notation. A unit of information taken with reference to the logarithm to the base two. This digit may be only 0 (zero) or 1 (one). It may be equivalent to an "ON" or "OFF" condition, a "YES" or a "NO", etc. One unit of information.

BLOWN JACKET: The common term given to an outer covering of insulation of a cable, that was applied by the controlled inflation of the cured jacket tube and the pulling of the cable through it.

B.M.D.: Ballistic Missile Division of the West Air Defense Command in charge of certain specific Missile development programs on the Pacific Coast.

BOND: Electrical connection assuring a low impedance path, usually to ground, between metallic objects which do not normally carry current.

BRAID: A woven protective outer covering over a conductor or cable. It may be composed of any filamentary materials such as cotton, glass, nylon, tinned copper, silver, or asbestos fibres.

BREAKOUT: A breakout is the common name given to the exit point of a conductor or number of conductors from a cable of which they are a part. This point is usually harnessed or sealed with some synthetic rubber compound.

BUFFER: An isolating circuit used to avoid any reaction of a driven circuit upon the corresponding driving circuit; e.g., a circuit having an output and a multiplicity of inputs, so designed that the output is energized whenever one or more inputs are energized. Thus, a buffer performs the circuit function which is equivalent to the logical "OR."

BUNA RUBBER: A synthetic rubber made by polymerization of butadiene. Bura-N is a copolymer of butadiene and acrylonitrile ($C_3H_3N_3$). Bune-S is a copolymer of butadiene and styrene.

BUNCHED LAY: In a bunched lay conductor or cable, the stranded members are twisted together in the same direction without regard to geometrical arrangement.

BUNCH STRAND: A conductor in which all individual wires are twisted in the same direction without regard for geometrical arrangement.

BUREAU OF AERONAUTICS: A branch of the Navy Department which has cognizance of all Naval Air activities; is also custodian of some assigned specifications for all armed forces.

BUS: A path over which information or energy is transferred, e.g., an electrical conductor or line.

CABLE: A cable may be a small number of large conductors or a large number of small conductors, cabled together, usually color coded and with a protective covering or jacket.

CABLE ASSEMBLY: A cable assembly is a cable with plugs or connectors on each end for a specific purpose. It may be formed in various configurations.

CABLE CORE: The portion of an insulated cable lying under the protective covering or jacket.

CABLE PULLERS: Cable pullers are manufacturers of cable assemblies who fabricate them by pulling the conductors through a plastic, rubber orneoprene tube. A cable puller is also a tool for pulling cables through a conduit.

CABLE SHEATH: A cable sheath is a covering of rubber, neoprene, resin or lead over a wire or cable core.

CALIBRATION: To determine by measurement or comparison with a standard, variations between true values and the readings of an instrument.

CAPACITANCE (CONDUCTOR): That property of a system of conductors and dielectrics which permits the storage of electricity when potential differences exist between the conductors. Its value is expressed as the ratio of a quantity of electricity to a potential difference, in farads (microfarads). A capacitance value is always positive.

CAPACITIVE COUPLING: Capacitive coupling is the association of two or more circuits with one another by means of capacitance mutual to the circuits.

CENTIGRADE: A scale for measuring temperature on which water boils at 100°C. and freezes at 0°C. as compared to Fahrenheit on which water boils at 212°F and freezes at 32°F.

CHEMICALLY CURED COMPOUND: Chemically cured compounds are those compounds which are cured by chemical process rather than by heat and pressure. In other words, the basic compound is accelerated by adding chemical ingredients which when mixed completes the curing.

CHROMAX: Chromax is the trade name of Driver Harris Company for a resistance wire. It is an alloy of 35% nickel, 20% chromium and the balance iron. It was developed as a cheaper substitute for nichrome resistance wire.

CHROMEL-ALUMEL: The alloys used in making Chromel Alumel thermocouple wires. Chromel is an alloy of nickel and chrome plus 9 other elements. Alumel is an alloy containing nickel manganese, aluminum, silicon and 9 other elements. Chromel is non-magnetic; alumel is highly magnetic. Chromel is the positive wire, alumel is the negative.

CIRCUIT (ELECTRIC): The complete path of an electrical current. When the continuity of the circuit is broken it is called an open circuit; when continuity is maintained it is called a closed circuit.

CIRCULAR MIL: A circular mil is a unit of area equal to Pi/4 of 78.54 percent of a square mil. The cross-sectional area of a circle in circular mils is, therefore, equal to the square of its diameter in mils. A circular inch is equal to 1,000,000 circular mils.

COAX: Abbreviation for coaxial cable. A single solid or stranded conductor over which is extruded a dielectric material. An overall RF Shield of wire braid, Mylar-backed foil, or metal tubing is added over the inner dielectric material with an outer sheath of dielectric material extruded over the shield to form a protective covering.

COLD FLOW: See creep.

COLD MOLDING: Shaping at room temperature and curing by subsequent baking.

COLOR CODING: Color coding is the application of a colored jacketing material on the conducting wire. Also color coding may be accomplished by the application of helically striped color on the outer surface of a jacketed wire.

COLOR SHADES: These are the basic 12 colors as specified in MIL-STD-104, within certain limits of light and dark as shown on the color chips accompanying the standard specification. In the case of synthetic rubber insulation, polychloroprene (neoprene) nylong or compound-filled tapes, for circuit identification, somewhat wider limits will be permitted in color shades provided all colors in the cable are easily distinguishable from each other.

COMET C: Comet C is the trade name of resistance wire manufactured by the Driver Harris Company. It is an alloy of 30% nickel, 4.5% chromium, and the balance iron. It is used from low to medium temperatures.

COMMON-MODE INPUT: Common-mode input is defined as that signal applied in phase equally to both inputs of a differential amplifier.

COMMON-MODE GAIN: Common-mode gain is defined as the ratio of the common-mode output voltage divided by the common-mode input voltage.

COMMON-MODE REJECTION: The ability of an amplifier to reject a signal, common to both its input signals. Common-mode rejection (CMR) is the ratio of the applied common-mode input voltage to the equivalent normal-mode output signal it produces.

COMMON-MODE RESISTANCE: Resistance between input signal lines and output signal lines or circuit ground. In an isolated amplifier, this is its insulation resistance. Common-mode voltage and common-mode resistance have no connection with the common-mode rejection.

COMMON-MODE VOLTAGE: That amount of voltage common to both input lines. Usually, a maximum voltage is specified which may be applied without breaking down insulation between the input circuit and ground.

COMMUTATOR: A device which is analogs to a rotary switch with many contacts, each contact having a different signal. As the switch rotates each signal is sampled sequentially and is available at a common point, the wiper.

COMPOUND: A compound is the chemical union of two or more elements.

COMPRESSION MOLDING: A method of molding thermosets. Compound (usually preheated) is placed in an open mold, mold is closed, and heat and pressure applied until material is cured. This process can also be used with synthetic rubber materials.

COMPRESSIVE STRENGTH: Crushing load at failure divided by the original sectional area of the specimen.

CONCENTRIC LAY: A concentric lay conductor or cable is composed of a central core sourrounded by one or more layers of helically wound strands or insulated conductors.

CONCENTRIC STRANDING: Stranding in which the individual filaments are spiraled in layers around a central core. As a general rule, each layer after the first has six more strands than the preceding layer and is applied in a direction contrahelical to that of the layer under it.

CONDENSATION: A chemical reaction in which two or more molecules combine resulting in a molecule of greater density. For example, water vapor condenses to form water.

CONDUCTED INTERFERENCE: Caused by the coupling effect of capacitance, resistance, and inductance to the source of interference.

CONDUCTION: Refers to interfering signals that appear across the receiver input terminals because of leakage paths caused by moisture, poor insulation, etc.

CONDUCTOR: A conductor is a medium for transmitting electrical current. A conductor usually consists of copper, aluminum, steel, silver or other materials.

CONDUIT: A tube or trough for protecting electrical wires or cables.

CONFIDENCE LEVEL: Express (in %) the probability that a given assertion is true, that it lies within certain limits calculated from the data; a degree of certainty.

CONNECTOR: A mechanism used to unite two pieces of cable, both physically and electrically.

CONTINUITY CHECK: Continuity check is a test performed on a length of finished wire or cable to determine if the electrical current flows continuous throughout the length. Each conductor may also be checked against each other to ascertain that no short exists.

CONTRAHELICAL: In the wire and cable industry the term is used to mean the direction of a layer with respect to the previous layer. Thus it would mean a layer spiralling in an opposite direction than the preceding layer within a cable or wire.

COPOLENE: Copolene is a dielectric material used in manufacturing coaxial cable. Developed as a substitute for polystyrene. It is composed of polystyrene and polyisobutylene. Since it has undesirable characteristics, it has been replaced by polyethylene.

COPPER CONSTANTAN: Copper and constantan are two alloys used in making thermocouple wires. The copper is the positive wire and the constantan is the negative wire.

COPPERWELD: Copperweld is the trademark of copper covered steel wire manufactured by Copperweld Steel Company. It is made by an exclusive molten welding process whereby a thick copper covering is inseparably welded to a steel core. Copperweld thus performs as one metal. Hot rolling, cold drawing, pounding or temperature changes cannot affect it.

CORONA: Ionization of air surrounding a conductor caused by the influence of high voltage. Ionization and partial breakdown of the gas dielectric in the vicinity of a conductor due to a high voltage gradient. May or may not be accompanied by a faint purplish glow.

CORPS OF ENGINEERS: A branch of the Army in charge of construction on all military installations and specifically supervising construction of missile installations for the Air Force.

COUPLING: Coupling is the association of two or more circuits or systems in such a way that power may be transferred from one to another.

CREEP: The dimensional change of a material under pressure over a period of time.

CREEPAGE SURFACE: An insulating surface which provides physical separation as a form of insulation between two electrical conductors of different potential.

CROSS-SECTIONAL AREA OF A CONDUCTOR: Cross-sectional area of a conductor is the sum of cross-sectional areas of all the individual wires comprising the strand.

CROSS TALK: Is interference that arises from other signal wiring. Electromagnetic and electrostatic couplings exist between signal leads in close proximity, and this effect may be significant if the signal levels are very different.

CURE: To change the physical properties of a material by chemical reaction, the action of heat and catalysts, alone or in combination, with or without pressure.

CURING TEMPERATURE: Temperature at which a material is subjected to curing.

CURING TIME: In the molding of thermosetting plastics, the time it takes for the material to be properly cured.

CV: The abbreviation for continuous vulcanization. A process for applying and curing rubber and rubber-like material on a mass production basis.

CYCLE: The complete sequence of alteration or reversal of the flow of an alternating electric current.

DATA: Plural term collectively used to designate alphabetic or numeric material, serving as a basis of discussion; material may or may not be technical in nature. Information, particularly that used as a basis for mechanical or electronic computation.

DATA - REDUCTION: The art or process of transforming masses of raw test or experimentally obtained data, usually gathered by instrumentation, into useful, ordered, or simplified intelligence.

DATA-REDUCTION, ON-LINE: The processing of information as rapidly as the information is received by the computing system.

D.B. LOSS: The loss of a signal over a conductor expressed in decibels.

DECIBLE (db): Unit used to express the ratio between two amounts of power, voltage, or current between two points.

No. of (db) & 10 Log 10 $\frac{P1}{P2}$ = 20 Log 10 $\frac{V1}{V2}$ = 20 Log 10 $\frac{I1}{I2}$

The voltages or currents in question are measured at points having identical impedances.

DEGREE RISE: The amount of increase in temperature caused by the introduction of electricity into a unit.

DELAY LINE: A conductor that is made of a specific material in a specific size and length that will permit the delay of an electrical impulse for a predetermined specific length of time. The delay is measured in microseconds and micromicro-seconds.

DENSITY: Weight per unit volume of a substance.

DESSICANT: Water or moisture absorbent material used to prevent moisture from damaging packaged equipment or other merchandise.

DIELECTRIC: A non-conducting material or a material having the property that the energy required to establish an electric field is recoverable, in whole or in part, as electric energy. A vacuum is a dielectric.

DIELECTRIC ABSORPTION: That property of an imperfect dielectric whereby there is an accumulation of electric charges within the body of the material when it is placed in an electric field.

DIELECTRIC CONSTANT (SPECIFIC INDUCTIVE CAPACITY): That property of a dielectric which determines the electrostatic energy stored per unit volume for unit potential gradient.

DIELECTRIC LOSS: The time rate at which electric energy is transformed into heat in a dielectric when it is subjected to a changing electric field.

DIELECTRIC POWER FACTOR: An expression of the energy loss in an electric current due to the effect of the dielectric.

DIELECTRIC STRENGTH: The voltage stress required to puncture an insulation of known thickness (in volts per unit thickness or per mil).

DIELECTRIC STRENGTH (DISRUPTIVE GRADIENT): The maximum potential gradient that a material can withstand without rupture. The value obtained for the electric strength will depend on the thickness of the material and on the method and conditions of test. Usually expressed as a voltage gradient (such as volts per mil).

DIELECTRIC TESTS: Tests which consist of the application of voltage higher than the rated voltage for a specific time for the purpose of determining the adequacy against breakdown of insulating materials and spacings under normal conditions.

DIFFERENTIAL AMPLIFIER: An amplifier whose input leads are related to circuit ground and responds to differential signals.

DIFFERENTIAL GAIN: The ratio of the differential output signal divided by the differential input signal causing that output.

DIGITAL-TO-ANALOG CONVERTER (DAC): An instrument which converts digital information (e.g. 1's and 0's) into analog voltages which are proportional to the numerical value of the digital information.

DIGITIZER: An electronic device used in data acquisition which accurately converts into coded digital information analog input voltages.

DIRECT COUPLING: Direct coupling is the association of two or more circuits by means of a self-inductance, capacitance, resistance or a combination of these which is common to the circuits.

DISPERSION: The scatter of values.

DOUBLE SHIELD: Two shields, one over the other. Maximum coverage 98% for copper braid.

DRAIN WIRE: An uninsulated stranded or solid conductor which is located directly under a shield. This wire, since it comes in contact with the shield throughout the entire length of the cable, may be used to terminate the shield and eliminate a considerable amount of the inductive effects of spiral type shielding.

E. C. M. - Electronic counter measure: The use of equipment to prevent or induce jamming of electronic equipment, missile systems, radar, radio, etc.

EDWARDS AIR FORCE BASE: Air Force missile test center, located at Edwards, California.

EIA: Abbreviation for Electronic Industries Association; formerly RETMA (Radio, Electronic, Television, Manufacturer's Association).

ELECTROMAGNETIC INDUCTION - or INDUCTIVE PICKUP: Refers to interference coupled to the measuring circuit through magnetic fields.

ELECTROSTATIC INDUCTION: Sometimes referred to as capacitive induction, is due to the unavoidable capacitance between the instrument or its wiring and the surroundings.

ELECTRO-TINNED: Electrolytic process of tinning wire using pure tin.

ELONGATION: Elongation is the extension or increase in length produced by a tension load in a section of a test specimen between bench marks placed on it, and is either expressed as a percentage of the original length between bench marks or indicated by specifying a minimum distance between benchmarks.

ENAMELED WIRE: A conductor with a baked-on varnish enamel; may be 7 gage through 50 gage. It is usually used in winding motors, coils, transformers, etc.

ENERGY (ELECTRICAL): Energy induced by the movement of electrons through a conductive material.

ENVIRONMENT: Surroundings into which wire or cable is to be placed.

EPOXY: A potting resin used in bonding; such as to bond teflon wire to pot connectors to assure that they are moisture-proof.

EPOXY RESINS: Straight-chain thermoplastics and thermosetting resins based on ethylene oxide, its derivatives or homologs.

ETCHED WIRE: A process applied to teflon wire in which the wire is passed through a sodium bath to create a rough surface to allow epoxy resin to bond the teflon.

EXTERNAL INTERFERENCE: This is the effect of any electrical waves or fields which cause confused sounds other than the desired signal.

EXTRUSION: A method of applying insulation to a conductor or jacketing to a cable. The process is continuous. It may utilize rubber, neoprene, or a variety of plastic compounds.

FACILITY POWER SYSTEM: That portion of the electrical power distribution and utilization system on the secondary side of the main electrical service transformer(s) for the test facility.

FAHRENHEIT: A scale for measuring temperature. Water freezes at $32^{o}F$ and boils at $212^{o}F \doteq 0^{o}C$. $212^{o}F = 100^{o}C$.

FARAD: A unit of measuring Capacitance usually expressed in microfarads (Mfd) or micromicro-farads (MMfd).

FEP: An abbreviation for flurolnated ethylene propylene, a thermoplastic material used as a wire insulation. FEP has outstanding insulating characteristics and retains them over a wide range of temperatures and frequencies.

FILLER: Fillers are used in multi-conductor cable to occupy the interstices formed by the assembled conductors.

FLAME RESISTANCE: Ability of the material to extinguish flame once the source of heat is removed.

FLAMMABILITY: Measure of the material's ability to support combustion.

FLEX LIFE: The time of heat aging that an insulating material can withstand before failure when bent around a specific radius (used to evaluate thermal endurance).

FLEXURAL STRENGTH: The strength of a material in bending.

FOAM-POLYETHYLENE: A polyethylene compound which has been whipped in the presence of an inert gas. The resulting compound has a lower dielectric constant than does basic polyethylene.

FREQUENCY DIVISION MULTIPLEX: Process or device in which signal channel modulates a separate subcarrier, the subcarrier being spaced in frequency to avoid overlapping of the subcarrier sidebands, and the selection and demodulation of each signal channel on the basis of its frequency.

FREQUENCY SHIFT: System of telegraph telelypewriter operation in which the mark signal is one frequency and the space signal a different frequency. NOTE: CCITT recommends that mark is the lower frequency. Also, the difference between mark and space will vary in different systems, e.g. 170 CPS U.S.A., 120 CPS Europe.

FREQUENCY SHIFT KEYING: Frequency modulation of a carrier by a modulating signal which varies between a fixed number of discrete values (a digital signal).

GAS FILLED CABLE: Paper insulated lead sheath cable filled with gas which provides a self-supervised alarm system. There are three different types: Low Pressure, Medium Pressure, High Pressure. They may be installed in ducts, in air or buried directly.

GENERATOR: A generator is a machine used to change mechanical energy into electrical energy.

GLASS BRAID: Used to provide thermal and/or mechanical protection in the underlying insulation of certain types of conductors.

GLYPTAL: Glyptal is a tradename for an insulating varnish, such as coating on coils. It is resistant to heat, oil and to corrosive conditions.

GROUND: A conducting connection, whether intentional or accidental, between an electric circuit (or equipment) and earth, or to some other conducting body which serves in place of the earth.

GROUND, ANALOG: Associated with the input circuits of an instrumentation system. Analog ground circuits are isolated from one another and are connected together at only one point, (e.g. ground bus, plate, etc.) and then, if required, this point can be connected to earth.

GROUND BUS: A bus used to connect the number of ground conductors to one or more ground electrodes.

GROUND CIRCUIT: That portion of an electrical or electronic circuit which is kept at essentially zero volts with respect to the power supply voltages. This ground circuit is not necessarily connected to earth. An electronic circuit will perform whether or not its ground circuit is connected to earth.

GROUNDING CONNECTION: A connection (used in establishing a ground) and consisting of a grounding conductor, a grounding electrode, and the earth (soil) which surrounds the electrodes.

GROUND CURRENT: A current flowing in the earth or some other body serving in its place.

GROUND, DIGITAL: Associated with the data processing system digital circuits. This ground circuit takes the form of many paths from each circuit to the ground point. Unlike the analog ground circuit, as many paths to the ground circuit as feasible are used and may not be isolated from each other as long as no closed circuit loops are formed.

GROUNDED NEUTRAL: The neutral wire is metallically connected to ground.

GROUND LOOP: A path through which current may flow from any starting point through a system and back to the original starting point.

GROUND, POWER: The power ground as defined by the National Electrical Code is any electrical connection between power system conductors (usually the neutral conductors) conductor enclosure or equipment enclosure and earth with 25 ohms or less resistance to earth. This ground is for the protection and safety of personnel.

GROUND-RETURN CIRCUIT: A ground-return circuit is a circuit which has a conductor (or two or more in parallel) between two points and which is completed through the ground or earth.

GROUND PLATE: A plate of conducting material installed in an equipment rack as a common tie point for all ground circuits in the system.

GRS - (Government Rubber Synthetic): This is a government standard for Buna-S Rubber for jacketing and insulating compounds for military wires and cables.

GUARD SHIELD: A shield which surrounds the input circuit of an amplifier.

HARD DRAWN: A term that refers to the temper of conductors that are drawn without annealing or that may work harder in the drawing process.

HEAT ENDURANCE: The time of heat aging that a material can withstand before failing a specific physical test.

HELIAX: Tradename of a coaxial cable.

HOOKUP WIRE: Small wires used to hook up instruments or electrical parts, usually 12 ga. and smaller.

HYGROSCOPIC: Having the tendency to absorb moisture.

IACS: International Annealed Copper Standard

IMPACT RESISTANCE: Relative susceptibility of material to fracture by shock.

IMPEDANCE: The apparent resistance to flow of an alternating current. Generally expressed in Ohms.

IMPREGNATE: To fill the voids and interstices of a material with a compound. (This does not imply complete fill or complete coating of the surfaces by a hole-free film).

IMPULSE STRENGTH: The voltage breakdown of insulation under voltage surges on the order of microseconds in duration.

INJECTION MOLDING: A molding procedure whereby a heat-softened material is forced from a cylinder into a mold cavity to give a desired shape. Cure is obtained under heat and pressure.

INSTRUMENT GROUND: See GROUND, CIRCUIT

INSULATION RESISTANCE: The resistance offered by an insulating material to the flow of current resulting from an impressed DC voltage.

INSULATOR: A material of such low electrical conductivity that it will not support an electric current.

INTERCALATED TAPES: Two or more tapes, generally of different composition, applied simultaneously in such a manner that a portion of each tape overlies a portion of the other tape.

INTEGRATED DATA PROCESSING: Way to transform disjointed and repetitive paper work tasks into a correlated and mechanized production of information for any purpose.

INTERSTICES: A space between one thing and another, as between conductors in a cable.

IRON CONSTANTAN: A combination of metals used in thermocouples, thermocouple wires and thermocouple lead wires. The iron wire is positive, the constantan negative. A regular stock item at Standard Wire and Cable.

ISOLATED AMPLIFIER: A differential amplifier whose input signal lines are conductively isolated from the output signal lines and chassis ground. An isolated amplifier is a differential amplifier. The reverse is never true.

JACKET: An impervious covering over insulation usually rubber, plastic, cotton, neoprene or glass.

J BOX, OR JUNCTION BOX: A box made of metal which houses electrical power brought from a central unit. The power is then distributed to the required point.

JAN-C-17A: Joint Army-Navy specification covering coaxial cables used for high frequency applications as in radio, television, radar.

JAN-C-76A: Joint Army-Navy specification covering radio hook-up wire. Types: SRIR, SRHV, WL, and SRRF.

JPL: Jet Propulsion Laboratories, California Polytechnic Institute

JUNCTION OR THERMAL POTENTIALS: Can contribute to error and are of special concern in handling low level DC signals. Items such as the cable flexing noise that arises in the use of pH meters and ion chambers might be also placed in this category.

JUTE: A natural fibre of plant base formed into rope-like strands. Used in cables for filling the interstices, to give a round cross-section.

JUTE FILLER: Rope-like strands of material used in cables for filling in the interstices to form a rounded shape.

KARMA: Trade-name for a resistance wire composed of 74.5% nickel, 20% chromium, 2.75% aluminum, and 2.75% copper.

KEL F: Polymonochlorotrifluroethylene MIL-W-12349. High temperature insulation -55°C to 135°C used on hook-up wire, and for tubing where temperatures are beyond the range of PVC, and where resistance to solvents is needed.

LOSS FACTOR: Product of the dielectric constant and the power factor and proportional to the actual power in a dielectric.

MAGNET: A ferrous metal that has the property of attraction of other ferrous metals.

MAGNET WIRE: Insulated copper wire used for winding coils, motors, and transformers.

MARKER THREAD: A colored thread layed parallel and adjacent to the strands of an insulated conductor which identifies the wire manufacturer and often the specification under which the wire is constructed.

MEAN: The arithmetic average; $\bar{x}$ for a sample, $\bar{\bar{x}}$ for a population. Equals $\frac{\Sigma x}{n}$ x = sample, n = number of samples

MEDIAN: The value above which, and below which, half the values lie.

MEGAWATT: One million watts = one megawatt.

Mfd: The commonly used abbreviation for microfarad, one millionth of a farad, the international standard for the unit of capacitance.

MICA: A transparent silicate which separates into layers and has high insulation resistance, high dielectric strength, and high heat resistance.

MICROMETER: An instrument used for measuring usually in 1000th of an inch.

MIL: One 1000th of an inch. A unit used in measuring diameter of wire or thickness of an insulation over a conductor.

MILLIMETER: Unit of linear measure. Abbreviated MM. Equal to one thousandth of a meter.

MIL SPEC: A specification issued by the Armed Forces of the United States of America.

MIL-C-17C: Military specification covering most coaxial cables.

MIL-C-2194: Military specification for silicone rubber insulated, armored shipboard cable.

MIL-W-5086: Military specification for aircraft 600 volt electrical wire, 105° maximum temperature rating. There are three constructions viz:

Type I: First stranded tinned conductor, second primary insulation, PVC, Third extruded clear nylon.

Type II: First, stranded tinned conductor, second primary insulation, PVC, Third glass fiber braid treated with suitable saturants. Fourth, extruded clear nylon on Sizes 22 through 12, and braided nylon impregnated with nylon lacquer on sizes 10 through 4/0.

Type III: First, stranded tinned conductor, second primary insulation, PVC, Third glass fiber braid treated with suitable saturants. Fourth, secondary insulation, PVC. Fifth, extruded clear nylon Sizes 22 through 12, and braided nylon impregnated with nylon lacquer on Sizes 10 through 4/0.

MIL-C-7078: Military specification for shielded aircraft power cable, 600 V. Specifies that the inner conductor shall be to [illegible]-W-5086.

MIL-W-5274: Military specification for airc[illegible] insulated electrical wire. There are three constructions or types: Type I - St[illegible]ed conductor, PVC insulation, extruded nylon jacket, 600 V rating. Type I[illegible] - [illegible]randed conductor, PVC insulation, glass fiber braid, extruded PVC and extruded nylon jacket 600 V rating. Type III - Constructed as Type II, 3000 V rating. Specification calls for surface marking showing government designation, manufacturers identification, wire size and year of manufacture at intervals of not more than fifteen feet.

MIL-W-8777: Covers 600 V, 150°C power and lighting wire. Construction: Silver-plated conductor, silicone rubber insulation with protective cover of braided or extruded material. Additional coatings as needed.

MIL-W-7139: Mil[illegible]ry specification for 600V, 400°F wire. Construction: 1st, silver coated copper stranded conductor, then laminates of teflon and glass.

MIL-C-8721: Air Force specification for m[illegible]niature coaxial cables RG 178/U, 179/U and 180/U.

MIL-16878: All types. Covers wire intende[illegible] for internal wiring of electric and electronic equipment. Temperatures range from 80° to 200°C. Potential ratings from 75 V to 3000 V. Type B - Stranded TC Conductor, PVC insulation 600 V 100°C Sizes 32 through 16. Type C - Standard TC Conductor, PVC insulation 1000 V - 100°C Sizes 24 through 14. Type D - Stranded TC Conductor, PVC insulation 3000 V - 100°C Sizes 24 through 6. Type E - Stranded SP Conductor, teflon insulation 600 V - 200°C Sizes 24 through 10. Type EE - Stranded SP Conductor, teflon insulation 1000 V - 200°C Sizes 24 through 10. Type FF - the same as EE, except for silicone insulation and it comes in Sizes 24 through 10. Type N - Stranded TC Conductor, nylon insulation 75 V - 80°C Sizes 32 through 20.

MIL-C-25038: Military specification covering high temperature and fire resistant cable. Nickel clad conductors, maximum temperature 750°C, outer braids and protective coverings as needed. Braids and coverings are usually teflon, asbestos, and glass.

MMfd: Common used abbreviation for one millionth millionth of a farad.

MODE: The most frequent value. Peak on the frequency-distribution curve.

MULTIPLEXER: An electronic device which electronically scans a number of parallel input channels and provides a serial output signal which is composed of a series of analog voltages representing a continuous sampling of each input channel. Its function is the same as a commutator.

MYLAR: A molecularly orientated polyester film with very high dielectric and tensile strength manufactured by the E.I. du Pont de Nemours and Company. It is normally used as tape wrap over a cable bundle.

NAS-STANDARDS: National Aerospace Standards. These are specifications compiled on different items by the Aerospace Industries Association of America, Inc.

N.E.C.: National Electric Code, which stipulates the use of wire and cable in buildings and factories. Most city electrical codes are derived from it. It has been compiled by the fire underwriters and wire and cable manufacturers.

N.E.M.A.: National Electrical Manufacturers Association. It is known for its standardization of electrical motors, components, and wire and cable specifications.

NEOPRENE: A trade-name of E.I. du Pont de Nemours for polychloroprene, a rubber-like compound which is known for its resistance to the effects of oil, solvents, and abrasion.

NEOPRENE TUBING: Used by cable pullers as a jacket.

NICHROME: Trade-name for an alloy of 60% nickel, 16% chromium and the balance steel.

NICKEL CLAD COPPER WIRE: A wire with a layer of nickel on a copper core where the area of the nickel is approximately 30% of the conductor area. The nickel has been rolled and fused to the copper before drawing.

NOISE: Any electrical interference present in a measurement signal which does not contribute useful information relative to the measurement signal.

NON-CONTAMINATING: Refers to a type of PVC jacketing material whose plasticizer will not migrate into the dielectric of a coaxial cable and thus avoids contaminating and destroying the dielectric.

NON-FERROUS: Term means not of iron, and refers to alloys which have no iron or steel as ingredients.

NON-HYGROSCOPIC: Opposite of hygroscopic - will not absorb moisture.

NON-MIGRATING: Means same thing as non-contaminating.

NORMAL MODE VOLTAGE: Actual signal voltage dev[illegible]ed by a transducer or the difference voltage between input signal lines.

NYLON: A generic trade-name by the E.I. du Pont de Nemours for synthetic fibre-forming polyamides; a polymer of nitrogen, carbon and oxygen. Its chemical unbalance and tendency to absorb moisture limit its use as a dielectric or insulating material. However, it is often used in the wire and cable field as a jacket over polyethylene or PVC to increase temperature stability and abrasion resistance.

NYLON-JACKETED: Refers to the [illegible]er covering of nylon or wire on cable which can be either an extruded layer o[illegible] a braid of nylon filaments.

OEM: Original Equipment M[illegible]ufacturer.

OIL FILLED CABLE: [illegible]aper insulated, leak sheathed cable, into which oil is forced under press[illegible]re, saturating insulation. Main object is to prevent moisture and gases from [illegible]tering. Also easier to detect flaws. Due to leakage (high grade mineral oil), kept under constant pressure at all times.

OIL FILLED PIPE CABLE: Basically the same as oil filled cable, but inside of rigid pipe, instead of lead sheath. Is sometimes a standard oil filled cable, inserted into rigid pipe, under pressure. Both units being oil filled. (Usually for much higher voltage. Kept under constant pressure at all times).

ON-LINE OPERATION: A type of system application in which the input data to the system is fed directly from the measuring devices and the computer results obtained during the progress of the event; e.g., a computer receives data from wind

tunnel measurements during a run, and the computations of dependent variables are performed during the run enabling a change in the conditions so as to produce desirable results.

OSCILLOSCOPE: Test instrument for showing visually the changes in a varying current by means of the wavy line made on a fluorescent screen by a deflection of a beam of cathode rays.

OZONE: A faintly blue, gaseous, allatropic form of oxygen, obtained by the silent discharge of electricity in ordinary oxygen or in air. It has the odor of weak chlorine.

PATCH CORD: Cord of varying lengths. Usually appearance braid covered with plugs or terminals on each end. Used to connect jacks or blocks in switchboards or programming systems. It is called a patch cord, because it is used to "patch".

PERMACORD: Crescent trade-name for rubber insulated, seine twine braid. Known as "Stage Cable". Is non-skid and is light brown in color.

pH: The measure of acidity or alkalinity of a substance. pH values run from 0 to 14, 7 indicating neutrality, numbers less than 7 increasing acidity, and numbers greater than 7 increasing alkalinity.

PIGTAIL WIRE: Fine stranded, extra flexible, rope lay lead wire.

PITCH DIAMETER: The pitch diameter is the diameter of the helix described by the strands or insulated conductors in any layer.

PLASTIC: High polymeric substances, including both natural and synthetic products, that are capable of flowing under heat and pressure into desired shapes and hardening in those shapes. There are two basic classes: Thermosetting and Thermoplastic.

PLASTIC DEFORMATION: The change in the dimensions of an object under load that is not recovered when the load is removed.

PLACTICIZER: A chemical agent added to plastics to make them soft and more flexible.

POLYAMIDE: A compound characterized by more than one amide group. The term is generally used in the wire and cable industry as a synonym for Nylon. See NYLON.

POLYCHLOROPRENE: The chemical name for neoprene, and used for wire and cable jacketing where the wire or cable will be subject to rough usage, oils, greases, moisture, solvents, and other chemicals. The name itself indicates that it is a polymer of chloroprene, a combination of vinyl acetylene and hydrogen chloride.

POLYESTHER: A resin formed by the reaction between a dibasic acid and a ddhydraxy alcohol.

POLYETHYLENE: A family of insulating materials derived from the polymerization of ethylene gas. They are basically pure hydrocarbon resins, often with small amounts of other additives to impart needed properties. All members of the polyethylene family are excellent dielectrics. Electrically they are far superior to any other extrudable solid dielectric in use today. Outstanding electrical properties include high insulation resistance, high dielectric strength, low dielectric constant, low dielectric loss at all frequencies, excellent resistance to cold flow, and good abrasion resistance. One or more members of the polyethylene family also have the following properties: resistance to sunlight, weathering, chemicals, flame. Polyethylenes are being widely used for insulation on telephone, signal and control cables, high-frequency electronic cables, high-and low-voltage power cables, line wire, neutral supported secondary and service drop cables. They are suitable for direct earth burial. Temperature ratings vary with type and application, from 75°C up.

POLYMER: The resulting compound formed by polymerization which sets up a union of monomers or the continued reaction between lower molecular weights.

POLYMERIZE: To change, by union of two or more molecules of the same kind, into another compound having the same elements in the same proportions, but a higher molecular weight and different physical properties.

POLYSTYRENE: A thermoplastic produced by the polymerization of styrenes, vinyl benzene.

POLYURETHANE: A copolymer of urethane similar in properties to neoprene. Usually used as a cold-curing molding compound.

POPULATION: In statistics, the entire group being studied, from which samples are drawn. This can be a production lot, readings on an instrument, tests on equipment, results of a test, ect.

PRIMARY INSULATION: A non-conductive material placed directly over a current carrying conductor, whose prime function is to act as an electrical barrier for the applied potential. It does not always have the purpose of abrasion resistance. See SECONDARY INSULATION.

PROTOTYPE: Original design or first operating model.

PURCHASE ORDER: The form used by a buyer from one organization to order material from another organization. Usually numbered. Can be confirming or non-confirming.

RADAR: Radio aircraft detector azimuth and range. General operation of a radar is to transmit a microwave signal at any azimuth 360° or any elevation 0° to 90°, bounce it off a metal object such as aircraft, or marine equipment; it then calculates the range from the pulse returned to the receiver and indicates this range graphically on a scope.

RADIATED INTERFERENCE: Caused by radiation of magnetic field from a transmitter and induced or "picked-up" by a receiver located at a considerable distance from the transmitter.

RANGE (R): Difference between highest and lowest observation.

REAL-TIME: The performance of a computation during the actual time that the related physical process transpires in order that results of the computations are useful in guiding the physical process.

REDSTONE ARSENAL: The U.S. Army's missile test and development center located in Alabama. Several Los Angeles firms do work there and purchase material for this work from SWC and Bucky Harris Company.

RELATIVE HUMIDITY: The ratio of the quantity of water vapor present in the atmosphere to the quantity which would saturate it at the existing temperature.

RESILIENT: The property of a substance to return to its original configuration after release of an applied force.

RESIN: An organic substance of natural or synthetic origin characterized by being polymeric in structure and predominantly amorphous. Most resins, though not all, are of high molecular weight and consist of long chain or network molecular structure. Usually resins are more soluble in their lower molecular weight forms.

RESISTIVITY: The ability of a material to resist passage of electrical current either through its cross-section or on the surface. The unit of volume resistivity is the OHM-CM; of surface resistivity, the OHM.

RETMA: See EIA.

RF: Abbreviation for the term "radio frequency". Usually considered the frequency spectrum above 10,000 cycles. (10 KC)

RF CONNECTOR: Connector used for connecting or terminating coaxial cable.

RG - Radio Frequency (Government): Prefix for coaxial cables.

RG 17/U: A coaxial cable having specific characteristics and construction. The prefix RG means "radio frequency government". The number 17 is the numerical assignment and U means for universal use.

RMS: Abbreviation for "root-mean-square". When the term is applied to voltages and currents it means the effective value, that is - it produces the same heating effect as a direct current or voltage of the same magnitude.

Example: $I_{rms} = I_{max} \sqrt{2}$

SAMPLE (X): A limited number of items selected at random from a population.

SECONDARY INSULATION: A non-conductive material whose prime functions are to protect the conductor against abrasion, and provide a second electrical barrier placed over the primary insulation or the shield.

SEGMENTAL CONDUCTOR: In single conductor cables 1,000,000 C.M. or more, the conductors are divided into three or four segments insulated from each other by paper tapes to reduce current resistance in AC circuits.

SELF-SUPPORTING AERIAL CABLE: A cable consisting of one or more insulated conductors assembled or cabled with a steel core or attached to a separate steel cable, which supports the weight of the cable. It may be from pole-to-pole or in a vertical position in a tower.

SEMI-CONDUCTING JACKET: A jacket having a sufficiently low resistance so that its outer surface can be kept at substantially ground potential by a grounded conductor in contact with it at frequent intervals.

SHEATH: The outer covering or jacket over the insulated conductors or provide mechanical protection for the conductors.

SHIELD: A metallic sheath placed around an insulated conductor or group of conductors to protect against extraneous currents and fields. Generally this shield is a metallic braid, but it could be spiraled copper, aluminum-backed Mylar tape, or conductive vinyl or rubber.

SHIELDED CONDUCTOR: An insulated conductor which has been shielded by a copper braid or tape, or aluminum foil, or copper foil, or a semi-conductive vinyl. The purpose is to confine the electrical field.

SHIELDED PAIR: A shielded pair is a twisted pair over which a metal covering has been applied. The metal covering is usually in the form of a bare or tinned copper braid but may be metal ribbon or metal backed Mylar tape.

SHUNT WIRE: A conductor joining two parts of an electric circuit to divert part of the current.

SIGNAL CONDITIONING: An intermediate means which includes all system elements that are used to perform necessary and distinct operations in the measurement sequence between the primary detector and end device. The intermediate means, where necessary, adapts the operational results of the primary detector to the input requirements of the end device.*

SIGNAL GENERATOR: A device used to furnish current at a known radio frequency, modulated and to deliver a measured voltage only at the terminals of the generator without appreciable radiation at any other points.

SIGNAL TO NOISE RATIO: Ratio of the power of the signal to that of the noise. This term is usually expressed in terms of peak values in the case of impulse noise and in terms of root-mean-square values in the case of random noise.

SILICONE: Polymeric materials in which the recurring chemical group contains silicon and oxygen atoms as links in the main chain. A thermosetting plastic material used for wire and cable covering, that is thermally stable and with electrical properties exceeding those of most organic polymers.

SINTERED: Usually refers to curing of teflon.

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* American Standard 30.11.045

SLEEVING: Tubed insulation used over wire or cable for insulation purposes such as vinyl; glass impregnated silicone; and teflon.

SOLDERABLE NYLON LITZ: Litz wire made up of Soldereze strands with a nylon serve overall.

SOLDEREZE: A trade-name for a magnet wire insulated with polyurethane base enamel.

SOLID CONDUCTOR: A conductor composed of one wire. Generally sizes 18 through 6, used where flexibility is not one of the requirements.

SONAR: Type of equipment used for detecting underwater sound waves.

SPECIFIC GRAVITY: The density (mass per unit volume) of any material divided by that of water at a standard temperature.

SPECIFIC INDUCTANCE CAPACITY (SK): Dielectric constant of insulating material.

STABILIZER: An ingredient added to some plastics, to maintain physical and chemical properties through processing and service life.

STANDARD DEVIATION (σ, S): Measure of the dispersion of values.

$$S = \sqrt{\frac{\Sigma(x - \bar{x})^2}{(n - 1)}} = \sqrt{\text{Variance}}$$

x = sampled value, n = number of samples, $\bar{x}$ = mean

STRAND: A strand is one of the wires, or groups of wires, of any stranded conductor.

STRANDED CONDUCTOR: A conductor made with a specified number of strands. Rope strand, for example, is a conductor made of multiple groups of strand. A 7 x 19 rope strand has 19 wires laid into a group and then 7 of such groups laid into a conductor.

SURFACE LEAKAGE: The passage of current over the boundary surfaces of an insulator as distinguished from passage through its volume.

SURGE: A transient variation in the current and/or potential at any point in the circuit.

SYSTEM ACCURACY: A measure of a system's ability to reproduce an input signal faithfully. If input signal is 10 V and the output signal is 9.99 V the error is 0.01 V and the percent error is 0.1% and the system accuracy is 99.9%. It is often common to specify accuracy in terms of percent error. In the above example this would be 0.1%.

TEDLAR: Trade-name of the E. I. du Pont Company for a polyvinyl fluoride film with outstanding weatherability and thermoformability properties. It has a high flex life over broad temperature range, with high tensile and dielectric strength.

TEFLON: Tetrafluoroethylene, better known as Teflon, the trade-name of E.I. du Pont, is produced by the total substitution of fluorine for hydrogen in the polyethylene molecule. This material excels all other commercially available thermoplastics in chemical inertness and operating temperature range, and is well suited for high frequency applications.

TEFLON COAXIAL CABLE: Coaxial cable constructed with a teflon dielectric.

TENSILE STRENGTH: The pulling stress required to break a given specimen.

TERMINAL: A terminal is any fitting used for making a convenient electrical connection.

TEST LEAD: Test lead is a flexible, insulated lead wire which usually has a test prod on one end. It is ordinarily used for making temporary electrical connections. The insulation is normally rubber, the standard colors are red and black. Test lead wire is a standard stock item at Standard Wire and Cable Company.

THERMAL CONDUCTIVITY: The ability of a given material to conduct heat.

THERMAL EXPANSION (COEFFICIENT OF): The fractional change in length (sometimes volume) of a material for a unit change in temperature.

THERMAL RESISTANCE: The resistance of a substance to conductivity of heat.

THERMAL SHOCK: The resulting characteristic when a material is subjected to rapid and wide range changes in temperature in an effort to discover its ability to withstand heat and cold.

THERMOCOUPLE: Thermocouples are pairs of wires of dissimilar metals connected at both ends, in which a voltage is generated due to a difference in temperature at the junctions. The voltage generated is of the order of magnitude of micro- or millivolts.

THERMOCOUPLE LEAD WIRE: The thermocouple lead wire is an insulated pair of wires used from the couple to a junction box or to the recording instrument.

THERMOCOUPLE WIRE: Wire drawn from special metals or alloys and calibrated to established specifications for use as thermocouple pair. For example: Iron, constantan, alumel, etc.

THERMOPLASTIC: A classification of synthetic resins that can be readily softened and resoftened by repeated heating, and reharden when heat is removed.

THERMOSETTING: A classification of synthetic resin which hardens by chemical reaction when heated and, when hardened cannot be resoftened by heating.

THIOKOL: Make from petroleum gas and used as a sealing compound for connectors, breakouts, etc. It has excellent electrical insulation and oil and solvent resistant properties.

TRANSDUCER: A device which converts the energy of one transmission system into the energy of another transmission system. A loudspeaker and a phonograph pick-up are [illegible] examples of transducers, the former changes electrical energy into a [illegible] energy, and the latter changes mechanical into electrical energy.

TRANSFORMER: An electrical device which changes voltage in direct proportion to currents and inverse proportion to the ratio of the number of turns of its primary and secondary windings.

TRANSISTOR: A transistor is a small unit composed of semi-conducting material. It requires no filament or heater voltage to operate and is very small. It replaces conventional radio tubes.

TRANSITE: The trade-name of Johns Manville Asbestos-Cement. It is made in pipe and fitting form, for use in building industry for use as electrical conduit.

TRANSMISSION LINE: One or more insulated conductors arranged to transmit electrical energy signals from one locality to another.

TRAP WIRE: A low voltage wire used at hinge points, where severe flexing occurs, usually in burglar alarm systems. It is made with tinsel conductor.

TRIAX: A type of shielded conductor that employs a shield and jacket over the primary insulation plus a second shield and jacket overall. Aside from applications

requiring maximum attenuation of radiated signals or minimum pick-up of external interference, this cable can also be used to carry two separate signals.

TV CAMERA CABLE: A portable, flexible cable consisting of several coaxial cables, and other conductors cabled together, overall shield and usually neoprene jacketed. It is used to carry signals between the camera and transmitter and plate and heater currents to the camera.

TWISTED PAIR (TP): Two insulated conductors twisted together and often color coded.

UF: Single or multi-conductor, with or without ground, used for direct burial underground feeders and branch circuits between buildings, yard lights, flood lights, and smaller installations.

UG: The two letter designation that precedes the number of connectors for coaxial cable. It means Universal Government.

UHF: Ultra High Frequency.

UL: Underwriters Laboratories Inc., chartered as a non-profit organization, maintains and operates laboratories for the examination and testing of devices, systems and materials as to their relation to life, fire and casualty, hazards and crime prevention. Founded in 1891, the enterprise is sponsored by the National Board of Fire Underwriters. It is operated for service, not for profit.

UL APPROVED: A product that has been tested to Underwriters Laboratories standards and approved by UL.

UMBILICAL CABLE: A lifeline cable used for the main power supply to the missile in order to launch it. It is attached by means of a connector which detaches as the missile becomes airborne.

UNSINTERED: Means uncured. This word is usually used to differentiate between cured and uncured teflon tape.

UTILITY POWER SYSTEM: That portion of the electrical power distribution system on the primary side of the test facility main service transformer(s) whether the system is operated by a commercial utility or by an agency of the United States Government.

VARIANCE: Square of the standard deviation $= \Sigma (x - \bar{x})^2/(n - 1)$
x = sampled value, $\bar{x}$ = mean (aritnematic average), n = number of samples

VISCOSITY: A measure of resistance to fluid flow, usually through a specific orifice.

VOLT: A unit of electromotive force.

VOLTAGE BREAKDOWN: Test to determine maximum voltage of insulated wire before electrical current leakage through insulation.

VSWR: Voltage/standing/wave/ratio. The ratio of the voltage maximum to voltage minimum which exists in a transmission line. Caused when there is reflection of incident wave, due to discontinuity or improper match to the transmission line.

VULCANIZATION: A chemical reaction in which the physical properties of an elastomer are changed by reacting it with sulfur or other cross-linking agents.

WORKING LIFE: The period of time during which a liquid resin or adhesive remains usable after mixing with catalyst, solvent, or other compounding ingredients.

WORKING VOLTAGE: The recommended maximum voltage of operation for an insulated conductor. Usually set as approximately 1/3 of the breakdown voltage.

YIELD STRENGTH: The lowest stress at which a material undergoes plastic deformation. Below this stress, the material is elastic; above it, viscous.

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